Eco-generative Design for Early Stages of Architecture

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Eco-generative Design for Early Stages of Architecture

Xavier Marsault

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Introduction

This book deals with “architectural eco-design”, a subject that is topical and fascinating, but difficult, because “in the drafting phase”, the designer has a wide range of options in front of him, but also a schedule, a certain number of constraints and rules that must be respected – and a barrage of uncertainties. This is why we have chosen to take “the generative approach” to help forge dynamic paths in these creative and promising spaces. In doing so, we address neither eco-construction nor eco-innovation, although they are closely connected to eco-design.

Architecture focuses just as much on the approach (the design process) as on the subject (analysis, study, construction, monitoring over time). Its subject of study is the structure, covering form, material, use and appropriate sustainability, all of which must come together to produce a building that is eco-efficient and pleasant to be in. It is discussed as the result of a project process based on the subtle balance between often contradictory decision-making criteria.

Elected representatives, managers, town planners, contracting authorities, architects and users navigate a constantly expanding universe of knowledge, often without the resources they need to understand its complexity and guide or explain their rationales, which are often a source of conflict. The fact that a large amount of knowledge is scattered and inaccessible to the people who have been affecting the environment through their choices for decades shows how urgent it is to produce tools that enable them to assess the impact of their decisions in a reasonable time frame.

A number of studies have questioned the conceptual, creative and innovative research phases of architecture and construction engineering. Most of these aim to define methods and develop tools that help with design and are likely to assist in the creation and production of more intelligently designed buildings. Digital instrumentation and support now have a vital role in this, and are the subject of regular studies and computing developments.

To meet the challenges of more environmentally responsible architectural production, for around 15 years, research has been enabling architects to access knowledge and tools from energy, environmental and constructive engineering, notably by means of digital simulation, a real interface between the engineer and the architect. Of course, we must acknowledge that specific tools for assisting with the design of efficient structures in the upstream project phase are only just starting to find applications outside laboratories. However, research strives to go further, proposing design support software environments that are better suited to the usual working methods of architects, attempting to preserve their autonomy and creativity.

The concept of efficiency, which is central to eco-design, runs through all the chapters. However, it is always "tricky to define efficiency in architecture, because it takes into account not only the objective and measurable qualities of an object, but also its relationship with its built or social environment, and the use to which it is put by users" [LAG 13]. Hensel proposes a redefinition of the concept of efficiency in architectural design, based on an analogy with biology [HEN 10]. We will return to this in the final chapter. This specific approach is different from previous ones, which either focused on questions of representation and meaning, or considered efficiency a synonym of function. According to current developments, efficiency is merely a level of requirement that must be reached retrospectively: energy efficiency, for example. But it could also be argued that the efficiencies that should be prioritized are those that have the greatest impact on the form and materiality of the structure.

In what follows, the four designations, namely *criterion*, *objective*, *efficiency* and *fitness*, denote one reality, seen, according to the case, from a qualitative or quantitative point of view.

What aspects should be prioritized in the upstream design phases? Which choices may be decisive, and what impact do they have on other aspects (formal, technical) that may influence the overall outcome of a structure?

We are going to examine the issues, possibilities and methods of eco-design, based largely on research and developments conducted within the French ANR *EcCoGen* project, which produced the EcoGen software program. Tackling the major difficulties of generative design head on in the interactive first stages of an architectural project (where the choices are the most decisive in terms of the overall and future efficiencies of the structure), EcoGen is interested in the behavior of structures in their constructed environment, through a generative and multi-criteria approach (morphological, energetic, atmospheric, functional, constructive) of eco-efficient design.

This book can therefore be considered partly as a summary of this project, which involved researchers from different laboratories, mainly the French CNRS's UMR MAP 3495 (Models and simulations for Architecture, town planning and Heritage). Several texts from the final project report[1] are cited to support and illustrate our arguments.

Finally, we will end with a discussion of the ambitious prospects combining some advances in the understanding of natural evolution with the desire to produce a truly bio-inspired theory of architectural morphogenesis. On this topic, the accounts provided in Chapter 3 should be linked to some of the bio-inspired prospects of Chapter 6.

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1 www.aria.archi.fr/wp-content/uploads/2014/11/Rapport-final-EcCoGen.pdf.

This morning, arriving at his office, Paul knows that a new stage of his life as an architect is about to begin. Yesterday, he received the new tactile creative tool from Microsoft, "*Surface studio*", equipped with a digital pen and control knob. He is one of the few in his profession to have this kind of equipment, although it is very affordable. His reason for turning to this modern solution, which encourages fluid design with tools that imitate freehand drawing, is called *Minos*. With this brand new software program, based on the integration of better technologies for designers, he knows that his ideas and creativity will transfer to the digital world like never before.

Minos registers Paul's tiniest line, slightest curve or smallest volume sketch in real time. Little by little, it comes to understand the ideas behind his project by comparing them with local and cloud-based databases, and then delivers the results of multiple calculations by means of a voice assistant, along with graphics that support decision-making. It can therefore quickly give Paul advice, direct him to eco-efficient choices, suggest that he alters lighting, structural elements or openings, etc. However, in addition to supporting the project with this active intelligence, from the sketching phase onwards, *Minos* is constantly learning from the user and familiarizing itself with his ways of drawing and designing. After a certain amount of learning, it will be able to suggest innovative shapes to Paul, without jeopardizing his creativity. As *Minos* is subtle and knows how to be discreet, *AI* is a winner! It can even share this knowledge with other online users, if Paul authorizes it. It's a real marvel!

Of course, just like the mythological hero after whom it is named, this software does not exist, or not yet. But are we very far from this kind of architectural design aid?

1

Context

"Sustainable development is based on three complex, related pillars: economic, ecological and social aspects, with the aim of moving towards practices, lifestyles and ways of functioning that protect the environment and the availability of the resources needed to ensure the survival of present and future societies. A good environmental approach will always seek a compromise between economic, social and environmental issues" (Olivier Coutard, in [COU 10]).

1.1. The environmental context

1.1.1. *Ecology: an ancient concept*

> "Ecology is an idea of the house, of the home – *oikos* in Greek means both ecology and economy. These two concepts have been combined from the beginning: *oikonomia* in Ancient Greek is the administration of a household, while *oikologos*, literally 'the study of the house', is initially defined as 'the science of the relationships between organisms and the world around them, i.e. in a broad sense, the science of the conditions of life' (Ernst Haeckel, 1866). Don't many of our current problems come precisely from the divorce between the two notions, the first constantly trying to free itself from the social requirements of the second?" [BÈS 14].

The concept of economics in the home is therefore not new. In the 17th Century, there were already simple solutions for coping with energy scarcity

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

and the difficulty of keeping warm. From the end of the 19th Century onwards, in a period of industrial expansion, engineers tried to use only the amount of material that was needed to produce objects, and thereby to reduce production costs. The past – even the distant past – is full of eco-oriented solutions that have often been wrongly abandoned by modernism [COU 10]. In addition, rural areas, which have fewer resources than large cities, have always demonstrated imagination and inventiveness in coping with adversity.

The so-called *environmental* approach is, however, more recent, especially with the joint increase in our technical resources for action in the world and their repercussions for a human population of more than seven billion. Eco-design appeared in the 1990s in northern European countries, following a three-fold realization: damage to increasingly weakened human populations and the environment, the gradual disappearance of fossil fuels and anthropogenic climate change. It became essential in the installation of energy transition [TIS 13], the responsible development of production and service activities, and resource savings at the heart of reflections on the built environment, also aiming to improve its efficiency.

1.1.2. *The Anthropocene and urban concentration*

During the period of history in which human activity has had the greatest impact on the environment (from 1850 to today), three major trends have emerged: a major increase in polluting industrial development, excessive consumption of material and energy resources by highly developed countries and the development of strong urban concentrations.

Due to the concentration of humans and their activities, urban environments are among the greatest drivers of past, present and future climate and environmental changes, and are also the social spaces that are most vulnerable to the consequences of these changes. "*In 2007, for the first time in history, the number of people living in towns exceeded 50%. It is likely to reach 60% in 2025, causing profound changes in large conurbations, because the urban explosion is accompanied by severe human and environmental problems, and is synonymous with precarious housing and increased poverty: one billion people were already living in slums in 2005*" (Nathalie Blanc, in [COU 10], Chapter 10, p. 171).

The Earth's resilience threshold was reached between 1960 and 1970, but the intensification of *greenhouse gas* emissions is likely to peak around 2020. They have accumulated in vast quantities for over half a century, and their effects will last for a long time, even after emissions have been dramatically reduced. "*We are beginning to depend on things that depend on the acts that we undertake, kindled, unleashed, in any case born out of our actions, like a new nature*" [SER 01]. Thus, we have entered the *Anthropocene* Era – a term coined in 2000 by the American geologist and biologist Eugène Stoermer and the Dutch geochemist Paul Crutzen. This neologism denotes a period in which human activities are having a real impact on the geophysics of the planet and climates, with the considerable risk of unbalancing them irreversibly. Let us partially conclude with Sabine Barles: "*experts say that we cannot return to former urban densities and morphologies. But we must start really thinking about how we organize and develop spaces so that their life and development are less harmful to ecosystems and the biosphere*" [COU 10].

1.1.3. *The increase in the Earth's temperature*

The International Energy Agency (IEA) confirms that by 2030, renewable energies will represent more than 50% of global electricity production, and annual greenhouse gas emissions should begin to stabilize, reaching 34.8 billion metric tons a year. In this period, corresponding to a phase of massive investment in the energy sector, the old thermal power plants will barely begin to disappear. If further efforts are not made after this date, global temperatures may increase by 2.6°C by the start of the next century [MIN 13], a figure much higher than the limit of 2°C beyond which the scientific community fears runaway climate change.

1.1.4. *Architecture and environmental thinking*

> "*At the end of the 19th century, architecture divided gradually into two schools of thought: the 'modern' school, which focused on the industrialization and globalization of architecture, and the 'traditional' school, which followed on from reflections on the qualities of regional practices. The modern school became dominant during the second half of the 20th Century, as post-war society dealt with an increased need for housing. This*

style began with the Bauhaus movement and developed from there, notably thanks to the architects Adolf Loos, Auguste Perret, Ludwig Mies Van der Rohe and Oscar Niemeyer. It was characterized by a return to minimalist decor, geometric and functional lines, and the use of new techniques. This movement was based on the idea that, in an increasingly industrialized society, architecture and design are functional elements. This movement had a lasting influence on architectural thought and made its mark on the entire century.

However, a second school, differing from the modern one, continued to follow vernacular architecture. More traditional and rural, this school was deemed outdated by society at the time. It had interesting values from an environmental point of view (use of local resources, consideration of context, etc.). It adapted to technological progress without reducing the existing regional qualities of the vernacular architecture. It is this school that inspired the concept of eco-design in architecture today" [GHO 11].

1.2. The energy context

Energy consumption has only been a major issue in the production and functioning of the built environment since the oil crisis in the 1970s.

1.2.1. *The energy crisis*

The energy crisis, which has received more and more attention since the last decade of the 20th Century, refers to the gradual disappearance of non-renewable primary energy sources, which still represent 78% of the global supply. Their consumption has doubled in 40 years, and, due to the inertia of the systems that we have put in place, the debts incurred for equipment, and our insufficient desire to change our behavior, the quantity of greenhouse gases emitted each year worldwide is not decreasing substantially [ADE 11]. However, to counteract the effects of the CO_2 emitted since the beginning of the industrial era, it should already have diminished by at least 25%.

Furthermore, the ecological imprint of all human activities on a global scale means that our use of resources is 35% above the Earth's capacities. Environmental issues are therefore playing an increasingly central role in architectural eco-design strategies and reflections on the built environment, with the aim of improving the efficiency of buildings in the upstream project phase, by integrating sustainable development parameters and constraints and taking legal and ethical imperatives into account. The 3x20 rule, fixed by a European Energy Efficiency Directive, aims to achieve the following by 2020: a 20% reduction in energy consumption, a 20% reduction in greenhouse gas emissions and a 20% share of renewable energies in the countries' final consumption. There are various methods and labels in Europe to structure and support the approaches and objectives that need to be reached (section 2.2 in Chapter 2).

1.2.2. *Energy consumption in houses*

Over the last 30 years, housing in industrialized countries has become much more energy efficient. However, living standards and the need for comfort are reflected in the fact that living areas have increased from an average of 25–38 m^2 per resident, thus significantly decreasing the savings made by their energy efficiency per square meter. The comfort temperature in well-insulated homes has also increased (above that fixed at 19° in France) since the introduction of the BBC (low-energy house) label, as has the tendency to open windows more readily in cold weather, to benefit from more ventilation. These effects, caused by comfort and reinforced insulation, have therefore led to an increase in energy consumption that sometimes reaches 30%, jeopardizing the commendable efforts that have enabled savings to be made (ultimately, only a 13% gain in homes between 1973 and 2006!). Finally, although there have been improvements in energy consumption and comfort, a new phenomenon has appeared: the steady growth in the use of electricity for specific uses other than those cited previously (consumption has increased from 13 kWh/m^2/year in 1973 to 30 kWh/m^2/year in 2010, although technical advances have greatly decreased the consumption of devices during the same period). Overall, it is easy to see why the building sector continues to consume massive amounts of energy and emit CO_2 into the atmosphere. We are far from reaching "factor 4".

1.2.3. *Strong measures*

The Rio Agreements (1992) and the Kyoto Protocol (1997) set objectives for limiting greenhouse gases, and France has committed to reducing the energy consumption of its buildings, which currently contribute 44% of the ultimate energy consumption (half of which is used for heating, ventilation and air conditioning) and 25% of greenhouse gas production. In light of this, France established two "Grenelle" laws in 2007 and 2010. These defined objectives and measures, notably for reinforcing thermal regulations, encouraging innovations and mobilizing society to save energy. *Thermal regulation* (TR) can be considered the cutting edge of energy control in new buildings in France. Requirements in this area are being gradually reinforced: average energy consumption of less than 110 kWh.EP/m^2/year in 2008, and a *low-energy building* (BBC) label corresponding to less than 50 kWh.EP/m^2/year in 2010 for public and commercial buildings, extended to all buildings in 2012, awaiting the *positive energy building* (BEPOS) label in 2018. Furthermore, in France, the Grenelle objectives were to make 38% savings in the sector of existing buildings from 2007 until 2020, based on 2005, and reduce greenhouse gas emissions by 75% in 2050, compared with 1990. In the wake of the *Conference of the Parties* COP2*, the latest energy transition law provides for a 40% drop in greenhouse gas emissions by 2030, compared with 1990, a 30% drop in fossil fuel consumption by 2030, compared with 2012, and a 50% reduction in ultimate energy consumption by 2050, compared with 2012.

1.2.4. *"Smart city" versus energetic city*

Optimizing electricity production and distribution depending on consumption and facilitating the network of local energy sources are at the heart of the current questions about energy saving. "*Centralized electricity production plants far from consumption sites are recognized as one of the main causes of global warming, due to major losses in transport*" [COU 10].

With this in mind, the *smart grid*, an energy component of the *smart city*, represents an intelligent approach of empowerment with the aim of managing local renewable resources better and, at the same time, promoting more restrained consumption. The general principle is to undertake urban transformations – technological, organizational and societal – with the main aim of developing optimized production, transport, mutualization and, potentially, energy storage services, while improving the everyday experience of inhabitants.

In practice, a *smart grid* is managed on an urban or territorial level through computing and control systems, with the aim of actively ensuring the functioning of each of its units in the face of fluctuations due to production sources and highly variable demand levels.

We will end with a distinction made by Christian Pierret, a former French Deputy Minister of Industry: "*energy production is not the only thing that transforms our environment – lifestyles and consumption patterns (transport, housing, food, etc.) do too. The realization is universal and affects both the rural farmer and the urban consumer, the least advanced countries and the major industrial powers*".

1.3. The technological context

In the construction sector, the progress that has been made, particularly in terms of insulation, ventilation management and regulation, implementation of efficient materials, and local energy production and mutualization, means that we are heading towards little if any heating in new constructions by 2018–2020. Excellent insulation is no longer hard to find. Taking inertia into account is more difficult, and is a fairly new aspect of the calculations. Detailed data and models are required to take thermal bridges into account.

Ventilation (even if it is natural) is much more subtle, just like all posts requiring active control. Regulation has become difficult but essential, and poor management of it can cancel out all the benefits of optimizing insulation, for example. Good regulation is based on complex outlines and activation models of technical mechanisms (including some that are highly empirical). The building therefore tends to become a highly technological object.

Dynamic thermal simulation requires knowledge of the precise occupancy patterns of each room. It is impossible to implement in the upstream phase, but some approximate models use it for simulation plans (Chapter 4).

Lighting is also a tricky aspect: we are gradually moving from a quantitative approach (lux, daylight factor, norm) to a qualitative approach (comfort, perception, dynamic lighting), using more and more technology.

Indeed, technical mechanisms can now be optimized, but this involves spending much more time working on software, which does not always facilitate the customer-centered approach. As for on-site implementation, this is essential and can also reduce great conceptual efforts to nothing.

1.4. The economic and social context

The architectural design process is notably characterized by precise phasing, regulated by the 1985 MOP law (relating to public building procurement and its relationship to private building procurement), which conducts conceptual research until the built structures have been accepted. Even if design and resolution work is carried out continuously, it is accepted that the initial sketching phases define the fundamental guidelines of the project. The choices made during this creative exploration are decisive, and reconsidering them later can be difficult and costly, and sometimes impossible. Furthermore, innovation, which is vital in the building sector, is generally reflected in an increase from 5 to 15%.

On the social level, energy insecurity is currently affecting 10 million people in France. Moreover, in old buildings, the investment costs for renovation are often too high for households with limited or non-existent financial capacities. The same is true for a large number of communities that are in a lot of debt.

A few positive points should be noted, however: ecological transition is a considerable technical and economic challenge for energy production, management and consumption lines, the development of which will create jobs, particularly when it involves taking advantage of local resources (biomass, geothermal energy, wind, water, agriculture, waste) and energy renovation works. Finally, we can hope that inhabitants will gradually gain awareness and take responsibility for managing their energy consumption, particularly in terms of more intelligent energy management and a circular, sustainable and more restrained economy.

1.5. The professional context

1.5.1. *The roles of the architect today*

Architecture must contribute to human well-being. Architects are tasked with making an enlightened contribution to improving living environments, by designing efficient, sustainable structures, mindful of their immediate and distant environment. By planning the shapes, spaces and atmospheres that make up an environment, as much through built structures as by the empty spaces that surround them, they promote architectural and urban quality, which is an essential ingredient of a sustainable environment.

The role of the architect within a project is both complex and varied. First and foremost, he is the original designer, the person who comes up with the concept or guides the design work. He is also the project management representative, which is probably the trickiest role to take on. Indeed, it is important to remember the context of cooperation: "*architectural quality is not the accumulated quality of all disciplines associated with design; what counts is the assertion of a global and consistent intention. In a sector in which each person tends to limit his responsibility and his intervention, the architect sometimes seems to be the only player who wants to reach this objective*" [MAL 01].

The architect must therefore make decisions and resolve disputes while respecting the legislation in force, the constraints of the site and those outlined by the Project Manager. His role goes beyond that of a negotiator within a network of players. He has the central role in the design, but also summarizes, coordinates, negotiates and moderates in order to keep everyone focused on the target: producing a coherent project. Appropriate software tools should facilitate the consolidation of choices from the first design phases, given that simultaneous consideration of multiple efficiency criteria increases the complexity of a construction or rehabilitation operation, necessarily requiring a systemic approach.

Furthermore, architects work in an environment driven by the digital transition taking place in a socio-economic sector that is already subject to the pressure of considerable changes: urban densification, increasing awareness of environmental and energy issues, social and economic crises, and a fiercely competitive industrial environment. In this context, designing sustainable buildings forces architecture and engineering agencies to respond to constantly increasing levels of technical requirements (proliferation of rules and standards) today, with increasingly fast decision-making processes.

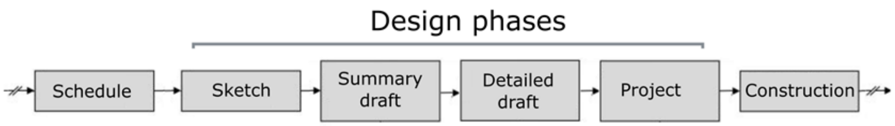

Figure 1.1. *The various design phases of a project*

Architects must therefore ensure that their buildings meet a certain level of efficiency, but they lack tools to help them design eco-efficient buildings from the first sketching phase, when formal and technical choices are decisive. The vast majority do not assess efficiency in the upstream phase, but in the detailed pre-project stage (Figure 1.1), when precise data has been sufficiently specified, resorting to specialized design offices, which increases the study costs and greatly limits the amount of back and forth and the number of variants. The problem is different for very large architecture agencies, which have internal engineering teams and their own software programs adapted to calculate more numerous variants (e.g. Gehry Technologies[1]). However, unlike in industrial design environments, the generative project approaches are fairly rare.

1.5.2. *Architectural design and the numerous constraints*

The use of digital modeling in the building design and construction process is called into question in the light of changes in the conditions and environments of professional practices. The strengthening of standards, the demand for sustainable design, the economic constraints, the emergence of external stakeholders in the decision-making process, and the agility and efficacy required of the parties involved in developing the living environment are all factors that significantly alter the operational contexts in which architects act. We might think that this complexification of contexts would lower the quality of architectural production, or, at the very least, hinder creative and innovative approaches, decreasing unnecessary risk taking. How do things really stand? This is one of the questions that will be discussed in this book.

1 www.gehrytechnologies.com.

1.5.3. *Issues that call into question the fields of development and the living environment*

This involves environmental issues (building better, with decreasing resources, polluting less, ensuring health and comfort), social issues (building for everyone – the role of the architect in developing comfortable, functional and sustainable living spaces – in a more urban style, with unevenly distributed resources, in an uncertain future), heritage issues (renovating, maintaining, preserving), cultural issues (creating knowledge, educating, preserving, disseminating) and industrial and economic issues (optimizing, promoting, selling, economizing). The environmental question in the field of construction and architecture became widespread in 1996 with *HQE* documentation, and has since led to a proliferation of labels, certifications and rules (section 2.2 in Chapter 2), whose profusion has sometimes been counter-productive. The need for a unified approach has recently led to the necessity of measuring the environmental efficiency of a building, notably through lifecycle assessment (section 2.3 in Chapter 2). The culmination of the overall eco-design approach (but also the object of many pieces of research), it aims to control the environmental impacts of any project, from its construction to the end of its life.

1.6. The instrumental context

In 30 years, computing has gradually become part of all aspects of design and creation. Digital tools are particularly used for their capacity to assist: virtual representation of a planned environment, analysis based on assessment and simulation of efficiency, and decision-making in the implementation of knowledge-based systems. However, these usage methods do have well-known hindrances and limitations in the creative design process associated with the initial phases.

1.6.1. *Transformational tools unsuited to the creative process*

First, we should note one weakness of the common tools (e.g. Archicad, AllPlan, Revit, etc.) that are still mainly used for creating and visualizing shapes and models, and precisely editing plans. Wrongly called computer-aided design (CAD) programs, these mainly help with drawing (2D, 3D) and representation of geometry, albeit in an increasingly sophisticated way. For example, 3D representation (with its possibilities of animation and immersion) makes it possible to assess the quality of shapes and spaces and check some dimensional constraints. Although the communication and verification contributed by these digital tools are necessary functions for the architectural design process, they should not be confused with the creative functions that are also required for the same process.

Furthermore, computer representation generally offers only a single level of reading, based on a geometric model, connected directly to the point of view that it prioritizes: external volumes, internal spaces, load-bearing structures and flow networks. According to Françoise Darses, the systematic assessment of CAD tools in the creative design process shows that they bring a sequential phasing of activities to the design activity. Information is collected from users to provide precise content, and executing the drawing takes precedence over analyzing the problem [DAR 94]. These "transformational" tools, which generally impose a predetermined resolution plan, reinforce the hierarchical planning of problem-solving and make it impossible to apply uncertain strategies and manipulate fluid objects, such as drafts, overlays and sketches. Their principle is based on translating functional and conceptual specificities into structural and geometric specifications to produce constructive specifications of the object. This makes them poorly suited to the characteristics of a creative process.

The fairly recent BIM (Building Information Modeling) guide does not contradict this assessment at all, but, because it facilitates exchanges around the digital model during the design phases, it makes it theoretically possible to delegate efficiency assessments to other software programs.

1.6.2. *A lack of assessment tools from the sketching phase*

Engineers naturally have more calculation tools than architects, essentially devoted to detailed projects. Software programs are also developed by researchers working in the field of architecture, for example, to optimize the orientation of buildings, the evolutionary generation of efficient envelopes [MAR 13b] or the construction of eco-profiles and eco-models to better understand the upstream design phase [GHO 11]. In these phases, which are always shorter and more intense, architects must increasingly ensure that the efficiencies required by law are achieved when their structures are delivered. For example, for the energy aspect, which predominates, a cross-disciplinary factor has several design features (orientation and volumetry of buildings, type of ventilation, lighting, heating, maintenance, etc.), the challenges of which are characterized by multiple spatial and temporal scales and by the interconnection between problems and constraints.

Numerous tools are used to produce a detailed simulation of the many behavioral aspects of buildings, including those related to energy. But they are based on sector-specific approaches and incomplete technical knowledge, and often require expert knowledge that is unusual in architects. Calculations are therefore performed almost exclusively by design offices, and have a significant accumulated cost.

One significant direction for research is obtaining effective operational tools that can carry out some of these calculations, even approximately, as early as possible. The designer benefits from being able to test more variants of his project and lower the engineering costs.

Finally, the current trend in the development of tools is openness to three pillars of sustainability (environmental, economic, social). Indeed, it is easy to build at a very high cost (e.g. prototypes for the *Solar Decathlon competition*[2]), which is out of reach financially for the vast majority of people. The economic aspect must therefore be integrated into eco-design tools as a key efficiency for the project, but it must also be considered over the lifecycle: this is the lifecycle cost approach [EIK 14].

1.6.3. *The need for computer-based modeling*

We can see a building as a complex system that interacts with a physical, human and social environment, which, in turn, acts on it. It is crossed by flows of energy, matter and people: it is therefore also a dynamic system. This combination of factors prevents us from predicting the precise development of efficiencies when we simply vary one criterion, such as the degree of aperture of the walls. An intuitive bioclimatic approach can turn out to be insufficient, even if it is inspired by relevant physical models. Only computer-based modeling can be used to overcome uncertainties as to the exact behavior of a building.

2 www.solardecathlon.gov.

The design process can then lead to an ongoing optimization phase. Different variants are tested and the most efficient selected and developed to achieve the initial objectives. It can take a long time to assess each variant if classic calculation software programs, which are sturdy but mostly very slow, are used. Furthermore, a recurring difficulty in optimization approaches lies in finding a compromise between contradictory objectives, such as increasing solar panels and the need for compact morphologies to limit thermal loss.

We therefore understand the need to produce tools that involve the designer in finding these solutions (to prioritize efficiencies, personalize solutions or simply preserve creative spaces), making it necessary to turn to interactive generators, which learn from their dialogue with the user (Chapters 5 and 6).

1.7. The programmatic context

Architectural design is distinguished from industrial design because its object exists in a geographically localized, and therefore unique, site. Therefore, although the structure may be identical from a construction point of view, its local context means that its design must be original (Table 1.1).

1.7.1. *Sketching and creativity phases*

The sketching phases mobilize a significant creative aspect that it is important to preserve. At the same time, they are crucial because they determine the main choices of the project, in terms of form, position, exposure to local climate conditions, patterns, spatial distribution of functions, organization and physical composition, and any technical systems. The decisions made have a great impact on many of the structure’s anticipated efficiencies.

Furthermore, the creative and innovative aspects of these periods of design must remain essential and their instrumentation must be part of a dynamic of creative stimulation, while also integrating efficiency parameters and criteria.

From the sketch to the summary draft, these phases combine an uncertainty as to the choices with a potential pursuit of innovation, involving new technologies, new materials, and new prototyping, production and implementation procedures. They define the fundamental guidelines of the project (Table 1.1), and efficiency should be sought as early as possible, rather than corrected later. Indeed, a project may reach a better level of efficiency through the addition of technical devices to correct design flaws or weaknesses (e.g. triple glazing on poorly oriented apertures), but these later re-assessments will be onerous and expensive.

Context and scheduling
– site and contracting authority;
– climate and weather contexts;
– urban constraints (template, orientation, position, capable volume (in the Koolhass sense) restricting construction (land use, height));
– usage type: public (school, hospital, etc.), housing, individual, mixed;
– programmatic data (surface area, volume, number of floors, % per usage type, % of openings on façade, roofing type);
– comfort parameters: thermal (winter/summer), aeraulics, humidity, light, acoustics, choice of energies.
Morphological possibilities
– architectural type: vernacular, standard, non-standard, etc.;
– differentiation: architectural approach/constructive engineering (in the upstream phase, the concept of a construction component seems premature);
– consideration of solar, acoustic or wind protection;
– work on the envelope of the building, rather than on the surroundings (uniform spaces);
– spaces and functions inspired by eco-models: atrium, conservatories, corbels, etc.;
– orientation, exposure, envelope, form, materiality: sun (winter inputs, summer protection), exposed/protected surface area, dominant winds, noises, existing/future surrounding facades, construction parameters.

Table 1.1. *Parameters and options for an architecture project in the sketching phase*

1.7.2. *Support tools*

At this stage of the design, the available tools are sturdy but slow, more appropriate for describing, simulating or assessing a solution than for assisting with the formulation of a proposal or stimulating creativity. Generative approaches are rare [MAR 12a, MAR 12b, MAR 13b], or implemented in an incomplete way. For example, an excellent eco-design support tool such as éco.mod [GHO 11] ought to be available in a generative version, like Alexander's patterns, on which it is based (section 2.6.4 in Chapter 2).

Furthermore, since environmental and energy regulations evolve faster than the training of those involved, designers often tend to be inspired by models that are deemed efficient for reaching regulatory objectives. Thus, when they plan, and when the data available at the time is patchy and imprecise, architects use quantitative criteria less often than qualitative mechanisms, which they test throughout the design process. This practice has notably led to: ignoring or practically ignoring the bioclimatic strategy behind a relatively efficient design, reproducing figures that hinder the production of innovative architecture, and an increasing and onerous complication of corrective systems (heating, air conditioning, artificial lighting).

Finally, the difficulty of designing and simultaneously resolving often antagonistic efficiency objectives – which normally require an *integrated design* approach – often leads to reliance on standardized solutions, a decrease in formal and material diversity, and a decrease in structural variety and architectural and urban quality.

Therefore, there is a clear lack of sketching support tools to enable architects to take efficiency objectives (relating to energy, the atmosphere, functions, construction, sensitivity, and the impact on the neighborhood and the environment) into account. These criteria are constantly increasing in number, and the calculation tools for assessing them are becoming more and more specialized. Knowledge of the interactions between phenomena is increasing, but this knowledge is scattered and not readily available or useable in the upstream design phase, despite the fact that it is here that the morphological, functional and constructive choices are the most decisive for the rest of the project.

Without claiming to produce revolutionary morphologies or ideal structures, a design support tool in the sketching phase should:

– make it possible to explore less conventional morphologies, better suited to their local context;

– promote a heuristic approach to a problem that makes it possible to explore unusual solutions while remaining accessible to non-experts, thus avoiding the use of calculation codes that are sophisticated and precise, but too slow and useable only in the advanced design phases, after enough data has been produced;

– make legible and comprehensible the complexity of the problems posed and the effects of the decisions made, notably by facilitating the visualization and analysis of the relationships between the parameters.

1.8. The cognitive, ergonomic and sensory contexts

> *"The more closely we can model our creative process, the more the computer becomes a simple tool for artistic creation, and less a replacement for inspiration"* (Bruce L. Jacob, [JAC 96]).

1.8.1. *Psycho-cognitive issues*

Studies in cognitive psychology have led to the identification of the ergonomic principles necessary for software developments in the upstream design phases [FLE 97]: facilitating body language interaction, enabling imprecise data to be entered, authorizing the transition between various levels of representation, facilitating comparison between different solution ideas, making suggestions, supporting assessment and facilitating the reading of morphology/efficiency interactions.

Other ergonomic aspects are essential if the tool is to be acceptable to architects, especially in an operational situation. Utility and, in particular, usability, integrating criteria such as processing speed, the reduction of unnecessary latency time, the capacity to trace the phylogenetics of solutions like a study book, and inclusion in the continuum of digital design aid tools, are ergonomic aspects that can be extensively studied, including through role-playing. The aim is to develop an attractive software solution, encouraging architects (professionals and students alike) to think creatively about the issues involved in sustainable construction.

Recent software tool developments have attempted to address these ergonomic principles, notably by improving the functionalities of human–machine interaction: multi-view manipulation of the geometric model, a modified representation or a representation that evokes the object using the appropriate graphic codes. However, transferring freehand drawing techniques to the digital field seems not to replicate the creative qualities of the sketch.

1.8.2. *Human–machine interfaces (HMI)*

The use of digital tools by those involved in design/construction projects is an entirely separate field of research. It is partly based on sociological foundations, but also on the compatibility of functions with "business needs". The development of the human–machine interface can be based on a user-centered approach. This method places the end user at the center of the design and assessment process [FAV 06]. It supports the specification of innovative visualization services [ZIG 11]. It identifies emerging practices based on the use of software tools specific to a real business activity. Furthermore, numerous models have been suggested, to address the various possibilities for HMI envisaged by researchers: user models, task models, usage models, dialogue models, presentation models and software architecture [LUC 05, VAN 93, SOT 05]. More recently, these approaches have focused on the collective aspects of practices and on proposing multi-visualization interfaces adapted to various parties [KUB 07]. A usage-centered method devoted to multi-visualization design in the context of collective activity has made it possible to propose multi-visualizations adapted to 4D (3D + time) simulation in the worksite planning phases [BOT 12].

1.8.3. *Stimulating the creativity of architects in the sketching phase*

If generative assistance software programs seem to significantly expand the range of decision-making tools available to architects, they create new design practices that enable environmental and efficiency-related qualities to be taken into account from the initial design phases. In return, these tools, which involve gradual construction of the architectural object, change the designer's relationship with his technical support environment.

Research aims to identify the capacities and limitations of these tools when it comes to contributing to a creative and innovative approach to architectural design. Defining the relationship between the designer and these instrumentation methods, it proposes generative software environments adapted to the first design phases, which preserve and stimulate the creativity of architects while guaranteeing a high level of efficiency for the sketched solutions.

One major concern is making project manager architects accept this kind of digital tool, which, rather than hampering their creativity, bolsters it by enabling them to explore solutions that are unusual on the morphological level, for example, but effective on the energy and environmental levels.

One of the objectives that we can expect of a high-quality generative tool is to spark the unexpected in the designer (the concept of serendipity is described, for example, in [AND 08]). If it proposes only logical, predictable, conventional solutions, it is probably limited from this point of view. The variety and originality of the solutions proposed are more important than their similarity to tried and tested solutions.

Here, the emergence of novelties or surprising solutions is the result of a process. The designer establishes the conditions for solution generation, but no longer undertakes the production of one exclusive solution: he makes choices based on all the possibilities available to him. For example, the criteria of habitability, constructive realism and structural complexity may be among the assessment methods available to the user, and must not necessarily be used for blind assessment of the efficiency of the solutions.

The Codisant laboratory, a research partner in the EcCoGen project, has worked not on an "intracranial" creativity, which is the responsibility of one creative individual, but on an in situ dialogue between a creative partnership and the tool. The dialogue process, sometimes through the intermediary of other tools (drawing, speech), is just as important as the result itself. It is therefore not the intrinsic creativity of the tool that should be assessed (its capacity to propose original solutions), but the interaction between the tool and the users (analysis of their creative behavior, see section 5.10 in Chapter 5).

1.8.4. *The comfort approach*

In terms of modeling the structure and its efficiency, the questions of energy consumption (ever-present since the first oil crisis) and of lifecycle assessment (the origin of the eco-efficient approach) cannot be the only things taken into account. An approach through normal comfort (light, thermal, visual, acoustic, in and around the building) and through quality of life (tangible comfort) can also be relevant [HUI 01], through the structure's effects on its immediate environment (shade, impact of the form on neighboring microclimates, air movements on contact with the envelope).

Unfortunately, the concept, characterization, modeling and monitoring of optimum comfort for occupants are rarely priorities when a building is designed. Regulations in France (RT2012) have begun to take well-being into account, but this concerns only summer comfort. It should be noted that in bioclimatic design, the question of summer comfort must first be dealt with from the point of view of ventilation and passive protections (near and distant) against the risk of overheating, before active solutions are envisaged (air conditioning).

Finally, there does not yet seem to be a tool that makes it possible to model the physiological parameters and overall needs of occupants and to understand the interactions between the various physical aspects of comfort, to assist the architect during design work, even in the later stages.

2

Eco-design

"*The human scale that is architecture is part of a global ecosystem where any action must be thought of and measured to avoid long-term disruption. Remember that the lifespan of a building is at least as long as that of a human being*". (Jean-Pierre Campredon, in [CAM 01])

2.1. Eco-design of the built environment

The architect Frank Lloyd Wright (1867–1959) was one of the rare forerunners of eco-design (*Levin House*, *Fallingwater*, *Usonian Houses*, etc.) and of the introduction of the concept of organicity in the project approach. But in the 1970s, environmental and ecological architecture, working with materials close to nature and interest in the relationship between humans and their natural environment, was still considered idealistic, despite the advice of some architects, such as Ken Yeang: "*a site must be studied from an ecological point of view to determine how best to develop the space without disrupting its natural equilibrium*". Gradually, over the next two decades, the idea of qualitative bioclimatic architectural design made headway, with varying degrees of success.

A significant step was taken at the start of the 1990s, with the emergence of the quantitative aspect of environmental eco-design for structures. Constructive efficiency, which had long been a synonym of resource saving, was then supplemented by environmental efficiency, which also creates

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

savings: it involves beginning to limit the impacts of our constructions on nature and living environments.

The first studies on life-cycle analysis and its methodological foundations began in 1992, but it is often forgotten that it was the economist David Novick who introduced the concept, which was initially used by the American army to improve budget management! Since then, "*eco-design has proven to be an approach that mobilizes numerous scientific contributions. It is based on the very simple principle of focusing on effectively reducing the flows generated by the functioning of a construction*" [GOB 11].

Finally, in our view, the main aim of *architectural generative eco-design*, which is the subject of this book, is to "*create bioclimatic solutions with a low environmental impact, contextualized, obtained by combining the multidisciplinary contributions of architecture, ecology, engineering sciences and computing technologies*" [MAR 16].

2.2. Eco-design: a continually developing process

The practice of eco-design was introduced to decrease the environmental impacts of human activities, starting with the most significant (energy consumption, the greenhouse effect, atmospheric and aquatic acidification, water and soil pollution, transport, waste). The 2002 technical report ISO/TR 14062 (International Organization for Standardization) generically defines eco-design as "*the integration of environmental aspects into the design and development of products and services*". In 2011, ADEME (The French Environment and Energy Management Agency) supplemented this definition with "*the desire to design products that respect the principles of sustainable development and the environment, resorting as little as possible to non-renewable resources by prioritizing the use of renewable resources, used with regard to their renewal rate, along with waste repurposing, which promotes re-use, repair and recycling*" [ADE 11].

Originally being the product of industrial environments in the 1980s, eco-design does not, therefore, imply merely using more or less sophisticated engineering tools. It is, first and foremost, a complex multi-criteria global approach, designed to support, guide and assist the designer(s) in producing sustainable objects, whether they are buildings, neighborhoods or whole towns [PEU 13a].

2.2.1. *Passive tool, labeling and reference documents*

Eco-design initially involved designing passive tools (reference documents for product assessment, material catalogs, certifications and labels) that could be used from the sketching phase onwards, with each country implementing its own rules in reference to international methodological ISO standards (14040, 14044), which were consolidated in 2006. Among the generic reference documents and labels are: HQE (France), then HQE-Performance, the French "*bâtiment biosourcé*" (biosourced building) label, given only to buildings constructed since 2012, which assesses the composition quality of structures, taking into account local ecological and economic assets; LEED (North America), BREEAM (United Kingdom), Bepos-Effinergie (France); and regulations (RT2012, and soon RT2018 in France). Then there are active tools used to solve a problem in the operational phase: *Éco.mod* (section 2.6.4), EcoGen (Chapter 5), ESQUAAS (*Esquisse architecturologiquement assistée*, architecturally assisted sketch), VizCab (section 2.6.5), etc., most of which are continuously developing.

The regulations and labels for energy and environmental quality focus mainly on the efficiency and sustainability of the building. They also increasingly require health control indicators to be displayed. Labels and regulations are constantly evolving as efficiency levels increase. Finally, recent labels, such as BBCA2, take into account the local context, which has not always been the case and could have a negative impact on the choice of construction materials.

The HQE and LEED tools are general guides adapted to an issue rather than to solving problems. They give guidelines but are not adapted to the specific features of the use case. LEED[1] is the American energy efficiency certification system in the construction sector. It has been regularly updated since it was created in 1998. Efficiency is defined by four levels of certification (2009).

The German *Passivhaus* label[2] sets four objectives: a high level of insulation, minimizing thermal bridges, passive solar gains and internal heat sources, excellent impermeability of the building's envelope, and good

1 www.usgbc.org/leed.

2 www.passiv.de.

internal air quality, thanks to the use of a mechanical ventilation system with heat recovery.

The Swiss MINERGIE label[3] sets several requirements: efficiency of the building's envelope, renewal of air inspected throughout the year, MINERGIE limit value, proof of thermal comfort in summer, additional requirements according to the building category (lighting, industrial refrigeration and heat production) and an extra charge of less than 10% for an equivalent program. The method used to attribute the label is set out in standard EN ISO 13790, equivalent to Swiss standard SIA 380/1. It compares the building's annual average consumption to an average value per type of program (e.g. 38 kWh/m²/year for housing).

The French BBC (*Bâtiment Basse Consommation*, low-energy building) label is inspired by the German *Passivhaus* label and the Swiss MINERGIE label. Other, stricter labels have appeared since, such as the Effinergie+ label (to respect a non-renewable primary energy requirement and an embodied energy threshold[4]) and BBCA [BBC 17].

2.2.2. *From HQE to HQE-Performance*

The HQE (1996) approach was the first certification document to include 14 targets divided into two groups from the start: controlling environmental impacts (G1) and obtaining a healthy and comfortable interior (G2). A 15th target addressing the issue of biodiversity was added later.

– (G1) eco-construction targets: harmonious relationship of the building with its immediate environment (C1), integrated choice of construction products, systems and processes (C2), and low environmental impact worksite (C3). Eco-management targets: energy management (C4), water management (C5), operational waste management (C6), and management of upkeep and maintenance (C7).

– (G2) comfort targets: hygrothermal comfort (C8), acoustic comfort (C9), visual comfort (C10) and olfactory comfort (C11). Health targets: health quality of spaces (C12), health quality of air (C13) and health quality of water (C14).

3 www.minergie2017.ch.
4 www.effinergie.org.

The move from “HQE approach” to “HQE-Performance” was a major evolution in regulations, developed jointly by the *HQE* organization and the *CSTB* (The French Scientific and Technical Center for Building), in partnership with industrialists and certification providers. Note the main developments: shift from the efficiency of components to the overall efficiency of the building; shift from the notion of building use to the notion of life cycle and shift from resources implemented to assess practices to reference documents based on calculated or measured efficiency indicators [ASS 15].

2.2.3. *“Passive building” label*

The PHPP (Passive House Planning Package software program[5]) is a validation tool for attributing the *Passive House* label. Working in Excel, this tool for designing passive buildings can be used from the sketching phase. It assesses efficiency indicators for passive construction: improved comfort, very low energy consumption, ventilation comfort, calculation of heating and cooling costs, summer thermal comfort indicator and reduced surcharge.

2.2.4. *BBCA label*

The latest version of the BBCA label (*Association pour le développement du Bâtiment Bas Carbone*, the French Association for the Development of Low-Carbon Building [BBC 17]) has been modified to include the measuring method set out in the Energy-Carbon reference document launched by the state (section 2.2.5). It sets more ambitious requirement levels and enforces additional “Climate Innovation” requirements that are essential for designing low-carbon buildings. The BBCA label has three efficiency levels: standard, efficient and excellent.

The label is applied to all buildings that use thermal regulation. Its scope is that of the building permit and includes the building and its plot of land. It may apply to several buildings if they are covered by a single building permit. It includes the building’s entire energy consumption during the operational phase, as well as water consumption, the worksite, and construction materials and products.

5 www.lamaisonpassive.fr.

The measure aims to establish the carbon footprint of the building and its greenhouse gas emissions throughout its life cycle. To achieve this, the BBCA label is based on a *life-cycle analysis* (section 2.3) that takes into account all these phases over 50 years. The emissions during the building construction phase are, for new buildings, higher than those during the operational phase (the HQE efficiency test indicates a 60% distribution during construction and 40% during operations).

The label is obtained based on the calculation of a unique efficiency score from prevented greenhouse gas emissions and carbon storage in buildings (high-potential fields of innovation, not yet integrated in life-cycle analyses). It makes it possible to reduce greenhouse gas emissions and gain time in the fight against climate change. This indicator highlights the quantity of biosourced material in the building, as well as the re-use of recycled materials and the use of recyclable materials at the end of the building's life.

The label highlights both the use of energies that emit minimum greenhouse gases and the use of low quantities of energy. It also highlights local energy production. Finally, it takes into account reductions in water consumption, which decreases emissions from transport and processing.

2.2.5. *Learning to think BEPOS (E+) and low carbon (C–)*

In France, *Grenelle Environnement* made a break in 2007 that reduced the primary energy consumption of new buildings by a factor of three between RT2005 and RT2012. In 2017, the positive energy building (BEPOS) is technically feasible for new buildings [GAR 11], but not for all budgets. It is probably a challenge for the next 10 years, not including the renovation sector.

Moving away from RT2012, which did not deal with all uses, we will gain no more than 25% in the next few years, because we are nearing our physical and technological limits, such as those of thermodynamic heat recovery systems in gas or liquid flows, for example. The maximum use of "renewable heat" will certainly bring substantial gains in terms of energy consumption, but there is still electricity. The third avenue is to work on restraint and efficacy for household uses, and to take the "technology side", using optimized active devices, which are low in energy, emphasizing their integration and control.

The problem is that, for the last 20 years, new uses have been being invented constantly, and we are always consuming as much or more electricity in a building (domestic appliances, electronics). Hence, the idea of making the building gradually autonomous in terms of electricity production, despite the difficulty of surfaces for solar panels being limited, make it necessary to increasingly pool energy through nearby networks.

Today, low carbon represents a challenge as difficult as that of decreasing energy consumption 20 years ago. Greenhouse gases are emitted by, in order: housing, transport, nutrition, services and health. Let us have a look at some figures. According to the “2000-watt society”[6], current greenhouse gas emissions are estimated at 7.2 t CO_2-eq/home/year and should be reduced to 1 t CO_2-eq/home/year by 2150. In France, emissions from heating systems in 2017 are estimated at 1.5 CO_2-eq/year/person. However, that is not the total carbon footprint, which is 4.2 t/occupied m^2. This is the figure that should be used in all calculations. Similarly, the current amount in a life-cycle analysis is 1 metric ton of CO_2/occupied m^2/50 years of a building’s life.

To reduce these CO_2 emissions and wasted resources significantly over the building’s life cycle, we can use three major guidelines (1–3), and three minor ones (4–6):

1) Energy-efficient and sustainable construction materials (section 2.2.7). The challenge relates first and foremost to having the right quantity, in the right place, a product whose E+C combination is the most efficient, with non-standard (or barely standard) solutions, but based as far as possible on the local context. For example, triple glazing is good for E, but less so for C (high embodied energy). We should also beware of confusing biosourced material and low carbon impact material: they are not always the same thing.

2) The use of renewable resources to generate additional thermal and electrical energy, moving towards energy self-sufficiency [EIK 14].

3) The types and methods of innovative constructions (e.g. prefabricated and/or modular, integrating the manufacture of items on the worksite through the continuous digital production chain, products prioritized by local SMEs).

4) Renovation produces an enormous carbon gain in relation to demolition and reconstruction [SCH 16]. In this sector, class G buildings

6 www.2000watt.ch/fr.

(thermal sieves) are a major renovation challenge when it comes to greatly decreasing E and C. An ambitious policy for the 35 million French homes that need to be renovated should be based on the example of new constructions.

5) A low rate of housing emptiness/vacancy should also be encouraged. The question of intensity of use is very important: an efficient BBCA block of flats ultimately costs a lot if it is empty! And yet, how many houses are empty in our country, in the town, in the countryside, on the coast and in the mountains? This, of course, raises the "highly political" question of how many new houses are really needed. Should we not first restrict owners and social landlords to a minimum occupancy rate? This is a controversial subject…

6) Finally, there remains the difficult question of guaranteeing the energy efficiency of solutions over time (which also has an impact on the depreciation of investments). Taking a gamble on the future of a piece of equipment beyond 20 or 30 years seems risky and can have a high cost in terms of manufacturing energy, and the results after this period will not be guaranteed, due to wear and tear to the materials. Furthermore, as research into circular economy is in its infancy, we do not know much about how recycling works in the medium and long term.

2.2.6. *The PEBN reference document*

The PEBN "*Performance Environnementale des Bâtiments Neufs*" ("Environmental Efficiency of New Buildings") document [RÉF 16], a preamble to the next RT2018 regulation (initially planned for 2020), is the latest French method for calculating environmental efficiency, based on life-cycle analysis of products and structures – a key tool of a low-carbon policy – with a definition of "gradual test thresholds": four for energy (E3 and E4 are highly efficient) and two for carbon (C1 is attainable for all). This document has been being tested since the end of 2016 by those involved in construction, through the introduction of a new "Energy-Carbon" label, the result of discussions between the HQE, Effinergie and BBCA organizations. This label is a prelude to the full and unique regulations for the major reduction of overall energy consumption (BEPOS objective) and greenhouse gas emissions over the whole life cycle.

Low-carbon-oriented life-cycle analysis is still a little explored area, but it will soon be obligatory in regulations, and manufacturers will have to supply reliable data on the "carbon weight" of their products and processes. We will then certainly identify other ways of moving forward.

2.2.7. *Environmentally friendly building materials*

A material is not environmentally friendly in itself. It may be efficient and even economical, but still not environmentally friendly (e.g. imported wood). Furthermore, "good solutions" from the past, even if they are environmentally friendly, can be unusable today: "*wanting to reuse old methods at any cost does not necessarily lead to savings, due to the current costs of certain implementations and the availability of noble materials*" (Gilles Perraudin, architect).

Only a practice can become environmentally friendly: the extraction (as local as possible) of a material, its implementation, its use and its maintenance can give it this status [BLE 14]. Of course, some materials, especially noble ones, do have some intrinsic environmentally friendly and economic qualities. The biosourced approach has become more successful over the last few years, with plant-based products (hemp, flax, straw, linen, wood, etc.) or animal-based products (feathers, wools, etc.), low in embodied energy (mineral materials, e.g. stone, sand, raw earth), from biomass, which are more insulating (cellulose wadding, cotton-linen mix from recycled textile fibers, straw-based walls, wood shaving walls, plant fiber panels) than their conventional equivalents. Note that "straw bales" are a regional renewable resource (especially in Normandy) with one hundred times less embodied energy than the conventional insulating materials; furthermore, they can store CO_2 and provide a high degree of thermal insulation. There is just one downside: many materials are still difficult to certify, such as straw, which is often excluded from labeling due to traceability difficulties. "*Building standards tend towards safety and efficiency, but a certain number of techniques and local or biosourced materials are not yet certified*" [MEN 14].

Conversely, some certified materials, such as aluminum, will never be classed as environmentally friendly materials, due to the highly significant quantity of embodied energy that they require (160,000 kW/h per m^3), while many builders still offer "highly efficient" wood-aluminum windows! For all this, not all metals have such bad statistics, and we can note "*a revival of metal construction (joinery, in particular), which has many advantages in terms of comfort, environment, safety, construction time, repair time and ease of expansion*" [MEN 14].

Savings are still expected for the materials of which glazing and thin insulation are made (e.g. silica aerogels), and significant research has also been done into optimizing them to obtain sufficient winter solar gains, while limiting them in the summer [MEN 14].

Finally, just because a material is known to be environmentally friendly, it is not necessarily usable in any construction project. Wood, which has been very popular in architecture over the last few years, is a very good example of this. Despite costing much more than traditional and/or synthetic materials, it has a very good efficiency/price ratio. Generally, this index is calculated by including the overall nature of the efficiency and cost indicators, to avoid too many technological but not very environmentally friendly innovations (e.g. *responsible insulation*, which is generally the case for wood).

2.3. Life-cycle analysis (LCA)

2.3.1. *The benefits of LCA*

According to ADEME, "*life-cycle analysis (LCA) is the most successful method in terms of overall multi-criteria assessment. It is the result of interpreting the quantified assessment of the flows of materials and energies relating to each step in the life cycle of products, expressed in terms of potential environmental impact*". It makes it possible to identify the main sources of impacts due to three contributors: materials, processes and treatments during their life cycle (acquisition of raw materials, production, use, end-of-life handling, recycling or scrapping).

Environmental impacts (multi-criteria standard ISO 14001[7]) are divided into three categories: impacts on natural and energy resources, impacts on surroundings (soil, water, air) and toxicological impacts on human health. These include: resource depletion (biotic, abiotic, energy), quality of ecosystems (biodiversity, eutrophication, ecotoxicology), land use, health

7 www.iso14001.fr.

(toxicology, fine particle pollution, etc.), impact on the greenhouse effect, destruction of the stratospheric ozone layer, acidification of waters (oceans, lakes, ponds, rivers, groundwater tables), biodiversity of biotopes and species [MEN 14]. In France, standard *NF-EN-15978*, from 2012, on assessing the environmental efficiency of buildings, sets out 20 indicators corresponding to the impacts listed above, including CO_2 emissions, for four contributors: construction and equipment products/energy consumption/worksite/water.

"*Most of the principles of eco-responsible construction are now found in LCAs: environmental record for design/manufacture and use, decrease in embodied energy, overall energy efficacy, carbon footprint, local savings, human and environmental ecotoxicity (health), reduction in waste and recyclability, and water footprint*" [MEN 14]. Furthermore, LCAs are now broken down into various scales: materials, components, buildings, road elements, urban property and neighborhoods.

2.3.2. *Main LCA software programs*

The complexity of processing an LCA make it vital to use a software appropriate for the study field, the available data, the expected results, their assessment (choice of a method) and their reliability (notably in terms of uncertainty analysis). But the compatibility of software programs/certifications cannot be taken for granted. For example, some software programs are compatible with French HQE certification but not with BREEAM, which is often used for office buildings in France.

The two main French software programs for LCA calculation are *novaEQUER* (developed since 1997 by the Ecole des Mines de Paris [PEU 13b][8]), and *ELODIE* (developed since 2008 by CSTB, using data from the *INIES* database[9]). Others include Bilan Produit, Eco-design Pilot and BEES. Bilan Produit[10] is an LCA software tool developed by ADEME and the Université de Cergy-Pontoise, and distributed free of charge to guide the optimization of a product according to its environmental profile. Eco-design

8 www.izuba.fr/logiciel/novaequer.
9 www.elodie-cstb.fr.
10 www.base-impacts.ademe.fr/bilan-produit.

Pilot is a qualitative, multi-criteria, free decision-making support tool, developed by the University of Vienna, in collaboration with ADEME. BEES (Building for Environmental and Economic Sustainability) is a software program combined with a database on the scale of the component containing the environmental impact. It was developed by the National Institute of Standards and Technology.

The main software publishers have understood the benefit of integrating an LCA tool (often a plug-in) into the digital design chain. For example, TALLY is an application developed by Autodesk for their Revit suite, enabling architects and engineers to quantify the environmental impact of construction materials for the complete analysis of buildings, as well as comparative analyses of design options. While working on a Revit model, the user can define the relationship between the BIM elements and the construction materials, based on a database provided by TALLY. As always, this assumes that the detailed project phase is underway.

2.3.3. *Associated databases*

The LCA is an evolutionary approach, a multi-criteria operational system and a decision-making aid, provided – as we have seen – that available and compatible software and databases can be accessed. Currently, a lot of environmental data have been collected in several standardized databases on the national or European scale. Knowledge of the environmental impacts of all human activities (or a particular sector, such as building) is still in its infancy, due to the complexity of the phenomena involved in the life cycle of the components and their treatment processes. But the last 20 years have given us more knowledge, experience and hindsight to help us find the best way to deal with the environmental aspects of sustainable development and its multi-scale dynamics.

This being said, obtaining data (materials, production processes, transport, lifespan, end-of-life prospects, recycling and waste management) is painstaking, time-consuming and costly. Many databases can be used to fuel LCA studies: general databases compatible with most LCA software programs (e.g. *Eco-invent*, the current global reference covering more than 4,000 entries relating to materials, products and processes for the various economic sectors (transport, energy, agriculture, construction materials, waste processing, electronics[11])), and specific databases, reserved for a particular field (e.g. the French *INIES* database deals only with building, but contains a lot of information[12]).

In France, data relating to building and construction products is provided in "*Fiches de Déclaration Environnementales et Sanitaires*" ("Environmental and Health Declaration Sheets", FDES). Each sheet contains LCA data and annexed information on health and comfort. These sheets are stored in the free *INIES* database, which, in June 2017, contained around 1,679 FDESs, representing around 35,000 commercial records for the French market.

Specifically, there are also PEP (*Profil Environnemental Produit* – Product Environmental Profile) sheets for electrical and climate engineering equipment. Manufacturers create PEP sheets to ensure that they are complying with the European regulation relating to the environmental declaration of some construction products used in building structures. It makes it possible to differentiate between the equipment concerned in the framework of "energy – carbon" experimentation by supplying environmental data for the products that will be used by those involved in building (contracting authorities and design offices).

It is important to know that, following a 2015 order that came into force on 1 July 2017, FDESs and PEPs must be verified by an independent third party. France uses two verification programs: "FDES vérifiées *INIES*" and "PEP ecopassport".

Finally, there is the international EPD (Environmental Product Declaration) system, a global program for environmental declarations based on standards ISO 14025 and EN 15804. Each EPD is a verified and recorded document that communicates transparent and comparable information on the environmental impact of products throughout their life cycle. The database that is currently online contains around 700 references for a wide range of product categories for companies in 36 countries[13].

11 www.ecoinvent.ch.
12 www.inies.fr.
13 www.environdec.com.

2.3.4. *Difficulties relating to LCA and its use*

1) As with any multi-criteria system, it would be unreasonable to expect to obtain a single impact score, especially as the 20 indicators are not ranked. "*There is no consensus on a general method through which the multi-criteria results of environmental analyses can be satisfactorily determined in view of relativizing or hierarchizing the significance of the various impacts generated*" [MEN 14]. Furthermore, as the analysis period covers several decades, it seems reasonable to be able to take into account variations of certain parameters over time. However, in each category, an intermediate impact score is often defined through weighting, to facilitate standardized comparisons, but the choice of coefficients may seem arbitrary and not very scientific.

2) Any impact calculation is riddled with uncertainties inherent in necessarily limited knowledge in a highly complex chain of causalities, in the simplification of calculation models, and in the different opinions of specialists and researchers. Furthermore, an LCA does not take into account all the potential impacts. For example, it is difficult to estimate pollution flows for a large number of interacting substances. Peuportier explains this complexity: "*among the pollutants emitted are more than 100,000 commercialized chemical substances, whose degradation over time emits residue into the environment (air, surface waters, groundwater tables, soils, etc.), but which are also found in food, because they are ingested by living organisms, with major consequences for health and biodiversity*" [PEU 13a].

Furthermore, "*each party knows only a small part of a necessarily interdisciplinary and cross-sector whole. Indeed, assessing environmental impacts requires knowledge from the fields of ecology, medicine, process engineering and energy, among others. Moreover, human activities involve interaction. For example, energy is required to produce cement, steel and concrete to produce energy, etc.*" [PEU 13a].

3) It is important to understand that improving the environmental efficiency of a stage in the life cycle can damage the efficiency of another step (characteristic of a transfer phenomenon in a complex environment).

4) Although building eco-design tools are progressing significantly, they are not spread widely enough that we could rely on them, as shown by [LAM 15], who attempts to determine the reasons for this. LCA is not yet adapted for the sketching phase; it is difficult to collect data from numerous

databases; and the results for a single structure are often different and not very reproducible, which reduces the user's confidence in the process. For more on this subject, see Lucie Genuys's work on the ANR-BENEFIS project [BEN 11], comparing the two flagship LCA software programs in France: *ELODIE* and *novaEQUER*, and the reproducibility tests [GEN 13]. Furthermore, the impact categories are not prioritized (which criterion to prioritize if compromises must be made); an LCA is expensive (€3,000–4,000 per variant), it is not highlighted enough in the certification process, and there is not yet a stable comparison reference to compare its results and determine the position of the project; finally, an LCA is always exploratory: no more than 25% precision in the upstream phase, while a robust LCA reaches 80% precision after the detailed project pilot. In addition, it should be dynamic in order to take into account changes in weather data during the study (from the design phase until work begins).

5) The introduction of LCA approaches into the design raises questions and concerns for some architects, particularly during the initial phases of the project. How can LCA become a decision-making aid criterion? To what extent can LCA methodology become a factor of design for the project manager, who is responsible for the sketch and defines the construction aspects, which have major environmental impacts that are not known at the time? Can building with less of an environmental impact still involve flexibility in terms of form and materials? Must LCA be limited to quantitative criteria, or, on the other hand, should it involve quality of life and atmospheres, which are standard components of the expertise of architects?

6) Approaching design from the point of view of "overall cost" is a relatively recent position for most people, with the exception of some eco-responsible architects, since the economic competition has for too long placed excessive emphasis on the financial variable. Finally, few architects and small agencies have adequate tools or sufficient resources or time to devote to full eco-design studies. However, it is estimated that 80% of the global costs during a product's life cycle are due to choices made in the first stages of its design, for which the effective design cost would not exceed 10%. This fully justifies taking time over it. Finally, even if it is problematic, one of the strong points of the LCA approach is that it verifies the environmental sustainability of architectural structures that are often proclaimed to be sustainable by their creators. Until it becomes obligatory… which will make things clearer, given the lifespan of the structures.

7) "*Circular economy is currently partly taken into account in the LCA with the use of recycled materials or products. But the rules applied make it impossible to fully appreciate elements such as the re-use of products, the sharing of spaces, and the potential for changes in use*" [GEN 13].

8) Finally, it is important to specify that environmental efficiency is only one aspect of sustainable development. Social and economic efficiencies (the two other pillars) are barely touched upon by LCAs (impact on human health).

2.4. Eco-design and BIM

BIM (Building Information Modeling) is a shared 3D digital modeling concept. "*Since 2010, it has built up and condensed everything for which parametric and associative software developments had paved the way over the previous decade*" [VAR 14]. Indeed, Lamé explains that the concept allows for an integrated view of the building, combining both its physical and its logical aspects. It facilitates and promotes the interoperability of various systems: drawing, CAD and assessment of efficiencies through physical models [LAM 14].

How can BIM support building eco-design? Although the phases following the summary project draft appear to be fairly well equipped, we have seen that the same is not at all true of the sketching phase. We may hope for the rapid emergence of a new generation of interconnected software tools, thanks to the unique BIM model, from the first project stages. An example is given in [SCH 09]: the authors use it to assess the efficiencies of a building project in the upstream phase of its design. Their approach consists of connecting the information on the building contained in the BIM to a calculator, which quickly produces a number of indicators that represent the required assessments.

2.5. Eco-design and efficient morphologies

The concept of eco-design also applies to the morphologies of built spaces. This section illustrates this, based on the themes of compactness, density and energy, which represent current issues in the development of urban fabrics and efficient architectural forms. We risk calling into question some well-established points of view (in reference: the copious study produced by the researcher Nikos Salingaros in [SAL 07]).

2.5.1. *Compactness indices of a structure*

Many studies have demonstrated the importance of morphology in the energy efficiency of buildings and towns [NOW 10, CAT 08b]. Studies into the compactness of buildings are the result of both seeking long-term energy savings and limiting investments, relating in part to the costs of the external envelope. Minimizing its surfaces areas can decrease the cost of the project and its maintenance. This reduction implies that, for a fixed volume V (in m^3), the surface area of envelope S (in m^2), constituting the walls in contact with the exterior (walls and roofs) of the contents, should be as small as possible.

Indeed, the more compact a building, the smaller the S, the less heat the building loses in winter, and the less it captures in summer. From a functional and constructive point of view, a compact structure facilitates circulation between its various parts, and its structure can be simplified. Finally, it should be remembered that compactness decreases most of the LCA flow emissions per square meter, with an impact that varies according to the type of energy used. However, the surface area available for solar panels is smaller, and it is harder to illuminate the interior of the building through natural light.

The compactness of a building, calculated by means of the S/V ratio, is mainly used by heating engineers: the lower it is, the more compact the building, and the smaller the amount of heat lost and the energy required to heat it. The problem with this formula is that it decreases when V increases, and different scales cannot be compared: this calculation is therefore not suited to architecture. We can therefore define two different factors of compactness, but both are invariable through homothety:

– S_{hab} denotes the inhabitable surface area, the index $C_h=S/S_{hab}$ represents *the exchange surface per square meter of the inhabitable surface area*: this is more appropriate for architecture;

– *dimensionless compactness* C, which is a shape factor in geometry, is calculated from the surface area of the envelope S, and the external volume V, according to the formula: $C = \frac{S^3}{V^2}$. In order to restrict the values to [0, 1], the index is compared with the minimum compactness of the sphere, which is equal to 36π: we obtain the standardized index: $Cn = \frac{36\pi}{C}$.

There are two methods for increasing compactness: either improving the shape so that the surface area of the walls increases less quickly than the inhabitable surface area (minimization of the exchange surfaces, buildings on several levels); or increasing C_n. Note that C_h and C_n are equivalent when the height of the stories is constant.

To conclude, the compactness factors must remain indicators of the bioclimatic quality of the design without being an obstacle to architectural creation. The question of cost aside, we can now construct buildings with a very high thermal efficiency, which are not necessarily very compact, affecting the quality of insulation, joinery and active systems (heating, ventilation). From an economic point of view, small homes are always penalized and must display higher thermal efficiencies and therefore higher construction prices per square meter. A fairly complete study of compactness factors in architecture can be found on the site[14]. It approaches the subject of passive houses in a highly methodical way, drawing conclusions that may initially surprise the reader.

2.5.2. *The influence of building height*

Very tall buildings are not sustainable. I know that it is not "architecturally correct" to say this. However, in Salingaros [SAL 07], the authors show that, beyond the effect of enthusiasm for modernism, and the prestige accorded to some architects and engineers, we must unfortunately admit that these buildings generate severe urban and social problems, as the architect Constantin Doxiades recognized more than 40 years ago. These include: congestion of urban services, isolation of individuals, property speculation due to the reckless increase in land prices in the neighborhood, very high construction and insurance costs, high energy costs, oversizing of networks for transporting material, water and energy; various dangers: fire, earthquakes, terror attacks, evacuation difficulties; increased risks: stress at work, high insanity rate, above-average crime rates; difficulty integrating

14 www.passivact.com.

into any type of neighborhood: destruction of the complexity and intermediary connection scales, visual pollution.

Is there a critical height? "*Urban forms made up of towers and low-rise buildings are generally not very dense, due to the size of the infrastructures required to serve them. Their energy assessments are not as good as those of old, dense centers. Thus, the traditional European urban fabric, made up of blocks of 3 to 6 stories, densely distributed to create a continuous fabric, with medium-sized roads, seems the most energy-efficient option*" [NOW 10]. This ties in with Salingaros's analysis: small towns consume much less energy than large ones, and there is a scale effect that produces a sort of critical size in terms of sprawl and height.

Finally, "*there is no correlation between demographic pressure and the rate at which such buildings are constructed, except in cities such as Monaco and Hong Kong, which lack space in which to build. Thus, the population of Paris doubled in the 20th century, and the city grew fifteen times in size. What our towns suffer from, therefore, is not a lack of space, but poor distribution of blocks, poor land use, and poor models and development schemes*" [SAL 07].

2.5.3. *Density, compactness, sprawl*

Towns have been significantly restructured in less than a century, for economic and transport reasons rather than to improve living conditions. This concern has not been forgotten, but is treated as a poor relation in certain parts of the world. Cities have become larger everywhere, due to the accessibility of personal vehicles (supported by a greatly expanding automobile economy) and the attractive pressure of commercial forces. It also occurs when too many buildings are erected with no understanding or consideration of the fabric of connections required to promote walking in towns.

However, beyond a certain size, towns encounter new difficulties in management and control, socially and economically, in terms of transport, food, material and energy supplies, pollution, and processing and removal of waste water, rain water and waste. Therefore, they are increasingly difficult to govern and cost a lot more in terms of equipment and functioning than medium-sized towns. Furthermore, there is a major gap between the apparently unavoidable challenges and the current range of solutions, which are often simplistic or narrow. The financial resources available and the timeframes for action affect the amount of debt per inhabitant in towns, narrowing the margins for future operations. Beyond a certain level of debt, these towns are not manageable.

If urban morphologies have a major impact on direct energy consumption, the founding works of the Australian Peter Newman[15] show that compact medium-sized towns appear to be the most virtuous in this regard. The notion of the compact town is the opposite of that of the sprawling town, but it is also not a dense town, or, still less, a hyperdense town. However, the profitability of significant investments imposes a design of urban fabrics in terms of energy density and not only of urban density.

According to Salingaros, "*the medium-sized compact town, ideally surrounded by agricultural land, will become dominant in the future, because it is the only viable alternative to sprawl, in terms of energy consumption and bottlenecks on the roads. An incremental strategy for reducing urban sprawl can be envisaged as soon as a new type of local economy (work, food and energy supply) begins to emerge, capable of recreating the diversity, links and connectivity in different fields and on different levels (forms, structures, existing infrastructures), and a certain permeability of the lines between the various sub-networks*" [SAL 07]. Thus, with a view to sustainability, mere densification is not enough: it must be accompanied by functional diversity, making it possible to bring together and combine areas for living, working, business and leisure, meeting most daily needs with no need to travel further than a few kilometers.

To conclude, there is a general consensus that we must escape this vicious circle of sprawl as soon as possible. However, soon, when fossil fuels have almost entirely disappeared and everything is renewable, will the compact town still make sense? The conclusions of the ANR MUSCADE project [MAS 09/14] are fairly lukewarm on this point. Perhaps, we should, conversely, prioritize medium-sized urban centers, which are not

15 tem.revues.org/pdf/260.

necessarily very dense but are fairly compact, and meet the criteria of alimentary and energy self-sufficiency (local production and sharing).

2.6. Examples of software environments adapted to generative eco-design

The first pioneering experiments in generative design in the field of architecture were performed by Frazer, Gero, Coates and Soddu. Frazer worked on the growth mechanisms of architectural forms through the implementation of generative techniques associated with notions of artificial life [FRA 95, FRA 02]. Gero took a cognitive view of evolutionary mechanisms, with the aim of modeling creative processes. He focused mainly on the representation of knowledge, the identification of novelty and the artificial transformation of the solution space [GER 91, GER 93]. Coates explored the implementation of L-systems and shape grammars in the light of morphological growth associated with efficiency criteria such as light, wind and structural properties [COA 10]. In addition, Soddu experimented with generative mechanisms as devices capable of generating a harmonious shape that meets academic esthetic criteria. He noted the major distinction between the design of the idea and the design of the generation process [SOD 04].

This section describes five eco-design software environments, developed in the field of architecture, during the sketching phase, in a generative, sometimes evolutionary mindset. A sixth, EcoGen, will be presented in detail in Chapter 5.

These examples enable two very different strategies to be defined: integrating various driving forces into a unique environment, and building links between distinct environments. The second has the advantage of using the specific features of each system, but has weak direct interactions during the generative process. For example, *Grasshopper* and *Ecotect* can be linked via the *Geco* plug-in, just as the UDP protocol can be used to communicate between *Grasshopper* and several software programs. However, building links between the various computing environments offers functional complementarity at the cost of complicating the system and increasing delays.

2.6.1. *Genomics*

Genomics relates to the optimization of a building's envelope to maximize solar absorption [BES 08b]. Here, the structure takes the shape of a tower with six stories defined by ellipses. Modifying its construction parameters allows for morphological exploration: width, length and orientation of the normal. The endmost ellipses remain unchanged. Restrictions, of the "minimum inhabitable surface area" and "maximum envelope surface area" type, are integrated and enable the functions of penalties and solution arbitration to be used.

The driving forces of assessment, generation and morphogenesis have been implemented in *Ecotect*, a software program for simulation and energy assessment from Autodesk: shadow and reflection, lighting, solar irradiation, thermal efficiencies and acoustic efficiencies. The user provides the software with a summary description of the structure, positioning the altitude of each level. The genetic algorithm is configured by means of a simplified interface. At the output, the program produces the geometric model, as well as the assessment report for the chosen individual. There is no interaction during the generation process.

2.6.2. *Building Synthesizer*

Building Synthesizer was developed by the Kaisersrot team at ETH Zurich, in a specific Cocoa environment (an Apple API), for reasons of efficiency, reactivity, interactivity and ergonomics [DIL 09]. The tool focuses on the automatic spatial arrangement of a defined program at a given site, and uses an evolutionary strategy. Based on the geometric, topographic and climatic description of a site, the space is subdivided into voxels (3D pixels). A number of points are distributed across the site. Their layout is not necessarily orthogonal, and the dual graph makes it possible to verify the adjacency links. The surface is then discretized. Each cell corresponds to a unit of the program. The level heights are constant and subdivision into voxels is repeated vertically at equal distances. Each voxel stores not only its geometric information but also its efficiency level. The distribution of these primitives and their geometric smoothing enables the final structure to be represented. The assessment driver is integrated into the software program for the sake of efficiency, interaction and ergonomics. The assessment model is made up of 10 parameter-quality pairs: information-permeability, temperature-insulation, light-translucency, view-transparency, sound-acoustic insulation, water-permeability, proximity-cost of circulation, weight-stability, depth-space and traffic-accessibility. At the output, a solution is represented in 3D and each efficiency level can be visualized. Throughout the process, the user can modify, interactively and in real time, the weighting of each assessment parameter.

2.6.3. *ParagenTool: performance-oriented design of large passive solar roofs*

ParagenTool was developed by Mickael Turrin and his team at Delft University of Technology, in partnership with the University of Michigan. *ParagenTool* is based on the engine described in Buelow [BUE 09] and aims to optimize a type of shade coverage whose structural qualities and quantity of filtered light are assessed. By developing links, the quantity of light is assessed by *Ecotect*, the structural qualities are verified by STAAD-Pro[16], the parametric model is built in *Generative Components*[17], the evolution is performed by a genetic algorithm implemented in a web service and the history of solutions is stored in an SQL database.

2.6.4. *Eco.mod*

Eco.mod is an environmental scenario generator, based on a "base of *eco-models*" or *eco-patterns*. It is dedicated to architectural eco-design and aims to promote the emergence of operational concepts and ideation processes in the upstream design phases. Eco.mod can also be used as a support tool for defining an environmental strategy to be shared by the members of an engineering team and the Contracting Authority. The tool is freely available online[18] (Figure 2.1).

16 www.bentley.com/en-US/Products/STAAD.Pro.
17 www.bentley.com.
18 www.crai.archi.fr/eco.mod/eco.mod/N1Accueil.php.

Eco.mod is a significant piece of research from the MAP-Crai eco-design laboratory (2008–2011), building on the work of Christopher Alexander on the role of *patterns* in architectural and urban design [ALE 77]. This architect mainly worked on establishing a "language of patterns" on all scales of composition. Using his grammar – the combinatorial rules and "generative codes" – this language produces a large number of possible scenarios. Alexander demonstrated, based on a mainly scientific and non-ideological concept of these patterns, how to design and produce healthy and lively urban configurations.

Design through *patterns* is a theoretical position on creation. Design patterns are a means of capitalizing on experience, making it possible both to identify and formulate problems and, at the same time, to find a result among many possible solutions more quickly. Generally, a pattern denotes a standard architectural form that can be re-used effectively, and addresses a recurrent problem in a given context. It describes a solution in sufficiently concrete terms that it can be used in numerous situations, but also sufficiently broad terms that it can be adapted to any context and never reproduced identically.

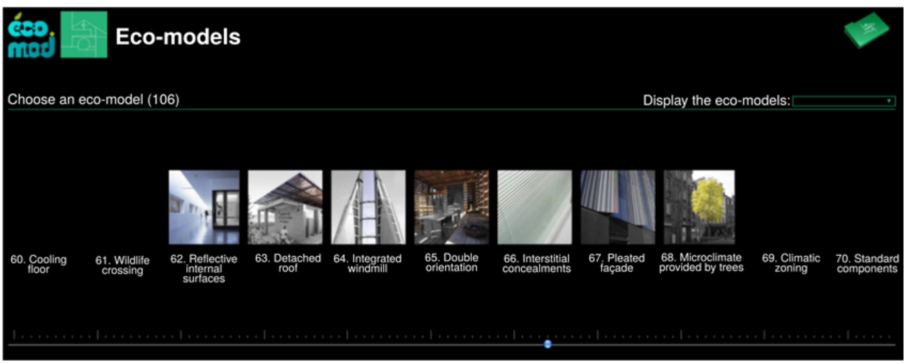

Figure 2.1. *Online éco.mod software*

Eco.mod uses visual thinking to stimulate the architect's creativity. An eco-model is defined by three aspects (problem, solution, constraints), illustrated by images of creations where it has been shaped in a unique way. The creations must have been recognized as ecologically significant by labels, book or reviews dedicated to environmental approaches in architecture. This threefold definition not only suggests solutions, but also clarifies some contexts required for re-using an eco-model.

The analysis and identification of a set of selected eco-models are used to fuel éco.mod's environmental scenarios generator. However, "*an eco-model is far from being a directly applicable solution. This concept has an abstract dimension that, incidentally, enables it to encompass one or more problems in the environmental design of buildings. Through this abstraction, it helps the designer to find solution/s through his own creativity. It represents an intermediary level of generality that defines the designer's intentions. This enables him to check that these intentions are acceptable as early as the upstream design phase, before embarking on detailed solutions*" [GHO 11].

The benefit of eco-models does not lie in isolated implementation. Constructing scenarios by combining them is a significant part of this approach. Eco.mod therefore tries to define the combinatorial rules between the eco-models. These rules help the designer to understand the relational context of each eco-model in order to integrate it into scenarios that are optimized from both an environmental and an architectural point of view. A bank of eco-models can also be considered co-creation of knowledge by parties who do not necessarily know each other.

However, the eco-model method does not specify how to find a solution to a problem. It depends greatly on the designer's creativity and intelligence. This distinguishes this method from generative approaches geared towards automation in design.

2.6.5. *VizCab*

This is the first software program, to our knowledge, that deals with LCA targets in the upstream project phase, using a generative method. It was originally based on an exploration method that made it possible to integrate life-cycle efficiencies into the early stages of the project design. Developed by the EPFL's Building2050 group[19], it was turned into an initial operational prototype called ELSA (Exploration tooL for Sustainable Architecture[20]).

19 building2050.epfl.ch.
20 elsa.epfl.ch.

It was patented by EPFL, and the company "*COMBO Solutions*"[21] obtained the exclusive rights to it following a technological transfer. It was developed into a SAAS-mode software program called "*VizCab*", which offers a design method based on *reverse engineering*, shifting knowledge and added computational value to the upstream rather than downstream phase of the project.

VizCab was designed as a parametric exploration of the complexity of the design space, where the user holds an interactive dialogue with the pre-calculated variants of his project. In the current configuration, the program limits the exploration to 20 parameters, thus avoiding a surplus of combinations that would increase the pre-calculation time.

The proposed approach makes it possible to instantly assess design alternatives by observing the environmental consequences of architectural choices through specific data visualization techniques [JUS 16]. This approach synthetizes a certain amount of expertise from environmental engineering and decreases the design costs.

VizCab was made efficient by an original combination of various techniques developed for this purpose: creation of optimized simulation databases, implementation of the *target-cascading* method [KIM 03, LIU 06] adapted to the scale of the construction, parametric simulations and sensitivity analyses (Chapter 4), and interactive visualization of variants.

Owing to the high number of parameters involved in assessing greenhouse gas emissions in buildings, it is currently impossible to calculate and analyze all the solutions in a reasonable timeframe. Therefore, VizCab first and foremost produces a wealth of references adapted to the current project, usable from the upstream phase onwards, simplifying the specifications. A reference is characterized by a combination of design parameters, each achieving targets (greenhouse gas emissions, embodied energy, heating consumption, etc.). These references are generated by a sampling method [MOR 91] based on a sensitivity analysis. In this upstream generative phase, each reference is subjected to a multi-criteria assessment, including energy calculations based on RT2012, the "E+C−" label (section 2.2) and LCA efficiency calculations.

21 www.combosolutions.eu.

Unlike tools such as EcoGen, which generate and optimize solutions with a detailed morphology “on the fly”, it is the user who explores this database, pre-calculated from simulations and simplified geometric models, in a transparent way, and then guides the tool.

Before using VizCab, the user sets himself or herself efficiency objectives for each overall target (e.g. those of the 2,000 W society or the E+C− label). Initially, the components of the structure are hierarchized according to their impacts for each target [HOX 16]. The *target-cascading* technique is then used to break down each overall target for building assessment into sub-targets for all its components. In VizCab, *target-cascading* is dynamic, specific to each project and to its pre-architectural aspect. Furthermore, manipulating weights for each component enables comparisons to be drawn with other components outside the database. Some items from the specification can even be eliminated in order to test the dynamic cascade effects.

The software program is then used as a baseline for visualizing solutions in multi-criteria graphics (Figure 2.2), showing which variants are viable when the parameters are interactively varied. An instantaneous snapshot of the whole base and of each specific reference constitutes a new way of quickly understanding the direct consequences of parametric choices on the chosen targets, the influences of their limits and the visual identification of the most significant ones. It enables rapid feedback, facilitating iterative design thanks to parallel coordinates visualization [INS 91], one of the most common techniques for exploring and interpreting a set of multidimensional digital data (Figure 2.2).

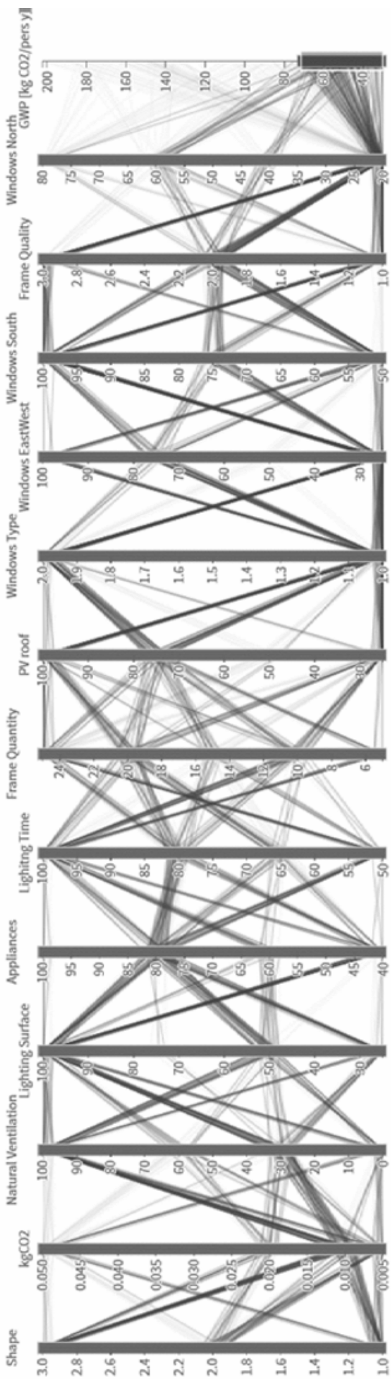

Figure 2.2. *Parallel coordinates visualization technology applied to the parameters of the building (upper line). On the right, a range of target values is selected, with references that correspond only to the pre-established objectives (e.g. "2,000 W society type") underlined in dark grey*

3

Morphogenetics

> *"Any built form is confronted with natural forms. The interest in natural forms leads to them being considered the result of generative processes. The invention of the form therefore becomes the invention not of an anticipated result, but of the process itself."* (Marie-Pascale Corcuff, in [COR 07])

3.1. Scientific formalisms of natural morphogenesis

Form generally denotes the outward appearance of an object, as it looks to our sensory organs, irrespective of its nature. The complexity of the world of forms means that they must be analyzed in their evolutionary dynamics, and the laws that combine the various components must be understood. This includes the conditions for their emergence and stability and the phenomenon of spontaneous and unpredictable self-organization of a set of components. We therefore refer to morphogenesis, which is discussed in numerous scientific works in the fields of biology, botany, physics, chemistry, mathematics and architecture. In this section, we will focus only on its natural aspects.

3.1.1. *Morphogenesis, growth and stability*

Osterlund [OST 10] gives an organic definition of natural morphogenesis: "*a process of development and evolutionary growth that forces an organism to develop its form thanks to the interaction of its intrinsic capacities and external environmental forces*". These capacities can be considered a *structure* that the organism uses to develop its own

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

identity, while remaining capable of adapting and evolving. Of course, we have not yet fully understood the nature of this structure, or of the evolutionary time frames. They are certainly *coded* subtly in genetic heritage, but probably also in the proteome (the set of cell proteins that enable the structure of the genome to be varied without altering the phenotype). They use complex cellular network interaction methods. In addition, each organism seems to have its own way of developing, although it inherits many characteristics from ancestral species.

In terms of temporal dynamics, Heudin [HEU 98] defines the stability of a form as "*a balance that returns to a state of systemic stability for a certain amount of time, during which its state variables remain stable*". Bourgine [BOU 06] distinguishes stable forms – those characterized by a transitory state in the midst of evolution – from those that require an external input of energy or matter to ensure their continued existence. Then, Baquiast [BAQ 04] adds an interesting precision: "*In physics, as in biology, evolution occurs in narrow ranges governed by the principles of thermodynamics and obeying the law of increasing entropy. To preserve or increase their order, they must save energy by using external sources. The forms that appear and survive are those that make the best use of the energy required for their construction and efficiency requirements*".

This certainly repositions Darwinism in a more global approach, which we can also link to Heudin's [HEU 98] variation-stabilization principle, preserving boundless opportunities of expression and adaptation for forms. There is a lesson here for those who claim that, in the field of building and urban planning, current restrictions and standards (of which there is certainly a large and regularly increasing number) are a hindrance to architectural design and a potential generator of uniformity on a global scale.

3.1.2. *Structure is law*

Natural morphogenesis does not generate random forms, although they may seem incredibly diverse. It obeys general laws and principles. Everything in the universe seems to be structured and governed by laws, from the very small to the very large. There are numerous spatial and temporal scales (pico, nano, micro, meso, macro), each with a set of laws and structures that are regularly discovered.

There are physical and chemical laws, but also restrictions to the development of complexity: random things do not emerge in random places. The number of forms – already very limited in terms of the huge number of combination possibilities – diminishes gradually as we move up through the levels of complexity. The number of typical galaxy forms is a good example of this, as is the number of mammals. However, even at the molecular level, the astonishing variety of possible atomic arrangements contrasts with the highly restrictive rules of the chemistry of proteins [CHA 06] – the materials that make up organic life – biochemical configurations and cellular types.

3.1.3. *Self-organization, Darwinism and structuralism*

Furthermore, for around 15 years, researchers have believed that self-organization dynamics, combined with Darwinian evolution (mutation, selection), explain the appearance, adaptation and stabilization of life forms. Matter is subject to the laws of physics and molecules to the laws of chemistry, and their combinations form complex systems that tend to self-organize. On different scales, they have a certain number of attractors: forms or structures that appear spontaneously (e.g. snowflakes), and are therefore determined by their emergence conditions. The phenomenon is therefore reproducible, and the chance is only one initiator. We can call these forms "structuring archetypes", which, beyond evolutions and adaptations, retain a degree of individual identity, often for very long periods of time.

"*This self-organizing push seems to restrict evolution to very definite directions*" (P.Y. Oudeyer, in [BAQ 03]), which may annoy all the Darwinists of the last two centuries. In consequence, some researchers are willingly returning to what is often called emergence, because the role of chance in the appearance of mineral and living forms now seems more minor than we realized a few decades ago. It is a wonderful subject that has already been discussed by, among others, the paleontologist Conway-Morris [CON 09] and the robotics and cognitive sciences researcher Oudeyer [OUD 13], who shows how natural selection is facilitated by the restrictions contributed by self-organization. Generally, structuralism seems to be the key, based on self-organization, many laws of which we are yet to understand.

3.2. Generation of forms for architecture

Let us first distinguish "architectural forms" (which refer to a classification of what already exists) from "forms for architecture", in which the challenge relates to analog but, above all, digital generation thanks to an increasingly wide range of informed processes, likely to stimulate creativity. Since the 2000s, with the spread of digital technology and the improved access to programming, architects have had access to new sources of formal research and inspiration for their projects [ROU 10]. This dynamic is shared by many artistic fields, first and foremost music.

Over 30 years, under the combined effect of mathematics and computing, the synthesis of forms has been enriched by procedural, parametric, surface-based, volumic and complex geometric models. Architects were inspired by this even before they became interested in the processes of architectural morphogenesis, which should legitimately rely at least on constructive, ornamentation-related and even bio-inspired rules.

Kolarevic established a categorization of digital techniques on the subject of form research [KOL 00]. He identifies six categories of computational architecture, based on the associated computing concepts: topological, isomorphic, animated, metamorphic, generative and evolutionary. We will not describe them all here.

3.2.1. *Classic form modeling typology*

There are many ways to model or generate forms, by means of:

– transformation operators of simple geometric primitives (typically implemented in current 3D modeling software programs), which can be cascaded in a random or predefined order;

– procedural synthesis: obeying the rules (potentially a very rich synthesis, but difficult to predict or control);

– the parametric approach (fixing the model/s for exploring new forms; lends itself well to adaptive optimization);

– continuous surfaces using "*NURBS*" (Non-Uniform Rational B-Spline), allowing a modeling of parametric families, usually described by means of topology. Intended for the conceptual research phases and appreciated for their fluidity and continuity, they are, however, far from suited to constructive resolution, which remains unintuitive;

– implicit surfaces, although they are fairly unsuited to architecture (with the exception of some modern buildings with organic appearances). However, they lend themselves very well to local and continuous transformations. One of the pioneers in this field, Greg Lynn, used isomorphic surfaces[1] as a formal exploration method, simulating interactions between objects that are generally called *metaballs*. Variables of force, mass and attraction enable us to explore a formal universe in which a force field can be parametered, defining influence and repulsion areas and thus forming a dynamic and lively landscape. The difficulty lies in avoiding a literal transcription of the flux and force diagrams present in an architectural form, and generating a spatial and temporal construction that ensures architectonic qualities [KOL 05];

– discretization of space, for example, into voxels (section 3.3), gives us the chance to approach all forms, but at the cost of fearfully long calculations and a considerable increase in the number of parameters.

However, it should be highlighted that we have not yet found a universal mathematical form generator. Johan Gielis's [GIE 03] seven-parameter super-formula [3.1] has proven very useful in many fields of engineering, but not highly suited to the creation of forms with architectural potential:

$$\rho_d(\varphi) = \left(\left| \frac{1}{a} \cos \frac{m_1}{4} \varphi \right|^{n_2} \pm \left| \frac{1}{b} \sin \frac{m_2}{4} \varphi \right|^{n_3} \right)^{-\frac{1}{n_1}} \qquad [3.1]$$

3.2.2. *Parametric architecture*

A parametric design process aims to define a set of variables involved in modeling a type of form or object in which we are interested. A parametric model is often built on the basis of relationships between geometric and/or functional entities, whose variables allow for the exploration of a vast set of solutions, integrating multiple dimensions (constructive, technical, economic, social, etc.).

1 glform.com.

Parametric design is a more recent approach, in which morphology is imposed by the parametric driver, and which makes it possible, sometimes very much upstream, to generate forms by integrating very precise restrictions, such as a logic of constructability and optimization of the design process. Although it has been previously reserved for exceptional projects, it now undeniably presents very strong potential for more conventional operations. Combined with simulation tools and optimization drivers, it can provide architectural and technical solutions in response to the outlined energy and environmental efficiency objectives [LIN 13].

3.2.3. *Techno-organic architecture*

Since the beginning of the 20th Century, some designers have based their form design and research processes on qualified techno-organic approaches. The principle is based on the interaction of three structural attributes: form, associated forces and matter used. Through the implementation of a simulation mechanism, the optimal form is naturally obtained under the effect of gravity and the internal structural tensions at play in the mechanism (e.g. soap bubbles). Le Ricolais, Gaudi and Frei Otto are the most famous representatives of this physically inspired approach. In a second phase, the analog models find direct architectural applications in constructions for covering stadiums, churches, hulls and concrete walls. These methods are based on the first "top-down" approaches, known as "form-finding", leading to a degree of structural optimization.

3.2.4. *An old debate*

In nature, "function follows form" is the response of structuralists. However, form adapts to new functions, which are often contextualized. This feedback shows that forms and functions are intrinsically linked.

However, for an architect who adopts the principles of functionalism, following the modernist movement and the industrial design trend at the beginning of the 20th Century, design is based on a rational principle according to which the form of buildings must be mainly the expression of their use ("form follows function", the famous formula of the architect Louis Sullivan). However, form always follows structure (animal skeleton, structural framework of a building [OKU 11]), and function is normally the result of an architectural program that describes, as a minimum, the uses to which the structure is expected to be put.

This old debate is always a controversial subject within the architectural community. It comes from a creative-adaptive interpretation of Darwinian evolution: “form follows function”. But is the opposite true: “function follows form”? The question here is which is first or causal: form or function? Perhaps the question is simply badly expressed, as is often the case with a complex system.

3.2.5. *Generative architecture*

The first generative mechanisms appeared at the start of the 1980s, following work carried out in the field of Artificial Intelligence [HEN 08, HEN 10]. Several families of structural algorithms were established for generative purposes. These use formalisms as varied as those proposed by thermodynamics, fractal geometry, Iterated Function Systems (IFS) [MAR 05], dynamic systems, cellular automata, form grammars (which have been explored since 1976 [STI 06] (particularly L-systems)), and multi-agent systems.

A form grammar is based on an iterative process leading to the construction of morphologies from one or several initial forms and a set of transformation or assembly rules, defining a vocabulary and a syntax. These methods often refer to space–times and state variables that are discrete or continuous, following deterministic or stochastic evolution patterns. They have been the subject of increasing interest with the development of digital design assistance tools.

Generative, and particularly evolutionary, design processes are distinguished by the fact that the role of the designer shifts towards that of a meta designer [SOD 04]. Architectural concepts are expressed in the form of rules, and their evolution can be rapidly tested. A digital model is transformed from successive variations and assessed depending on predefined aims and restrictions. The designer no longer works on elaborating an exclusive object but rather on designing processes capable of generating a family of forms, of which a chosen solution may represent a significant state within a set of potentialities.

The acceptability of a generative tool for an architect is based on the appreciation of the architectural and architectonic creative potential of the proposed solutions, and on its assessment of the margins of liberty and creativity that remain in the later redefinition phases. The proposed morphologies must leave room for reinterpreting the object in terms of style and materiality.

Furthermore, elaborating a morphological model in a generative environment meets four aims: being adapted to the requirements of physical efficiency assessment models (facilitated calculations and rapidity); facilitating the recognition of efficiencies and linking them to the morphological characteristics of the solution; facilitating (re)interpretation (functional, geometric, constructive, material) by the architect; facilitating possible interactions with the operator, who may manipulate the geometry and some properties of the solutions produced in order to calculate optimized versions.

3.2.6. *Performative architecture*

More and more research is taking a conceptual approach consisting of concretely testing form generation tools in order to define and validate a framework of morphogenesis based on efficiency criteria (energy, environment, usage, etc.). We thus move onto the logic of form finding, which is interesting because it makes it possible to link optimization to the theory of complexity, through the notion of computational emergence (bottom up).

This approach defines performative or *performance-based* architecture, in which the form results from a design process guided by an optimization of parameters and characteristics with meaning [MAR 10, STO 13]. The architect thus becomes the designer and/or controller of the generative processes, with the fear that he might lose control of the form if his intervention in the generative mechanism is too minor.

Conventionally, through many software programs, the simulation of the building's efficiencies during the design process allows for multi-criteria assessment of a project (usually quantitative, sometimes qualitative): structural, light-based, thermal, acoustic, environmental analyses, etc. Through successive tests, designers can adapt the form to the efficiency objectives.

But this approach through variants can be enriched by integrating a generative dimension that allows for software optimization of the project, notably form research with automatic adjustment of its characteristics. J.F. Blassel established that this approach is associated with a structural meta-design, in which the definition of criteria of choice and boundary conditions is just as important as the architecture of the structure [MAR 06].

Furthermore, we can also use the optimization process to explore a vast range of possible solutions, controlled by the user, so as to provide inspiration and identify useful solutions on various levels (performance-based, subjective, etc.).

The multitude of criteria that can be taken into account in the design stage, their prioritization and the various ways of calculating and using them is a tricky part of the method. These aspects characterize any optimization process in which satisfying a vast set of often contradictory fitnesses and restrictions is usually a challenge.

The quest for efficient "forms to build" is therefore part of a decision-making chain in which the skills of architects and engineers are mobilized simultaneously. Examples of creations instituting practices of optimization through collaborations between architects and engineers can be found in the book *Design Engineering* [TAY 08].

3.2.7. *Eco-design and morphogenetics of energy*

The rapid evolution of regulations has led to the recognition that energy modeling techniques must be integrated into the design process as early as possible. In its 2015 report, the American Institute of Architects suggests that "*the form of a building should at least be guided by energy saving calculations, if not entirely determined by them*".

However, this raises a few questions. How does integrating energy modeling into the design process affect the result? In other words, if we give the tool free rein to investigate the extensive range of optimized solutions in a given situation, what do the generated forms look like? Does energy efficiency optimization produce "forms of energy eco-efficiency" and new and characteristic morphologies?

More generally, are there more eco-efficient emerging formal vocabularies that are not simply linked to energy questions, but take into account a balance between overall functional objectives (thermal, light-related, acoustic and visual comforts) and energy efficacy?

Finally, is there still room for architects to be creative? Do we risk producing a normative vision that influences architectural production by limiting the creativity of the designer, who feels restricted, even stifled?

3.3. The specific case of the voxels approach

Voxel is the name given to the base unit of a subdivision of space into a regular and uniform mesh (3D grid). A contraction of "volumetric element", this unit can have varied properties: coordinates, color, material, function, etc. Voxels are often used in the field of imaging, for visualizing and analyzing medical and scientific data, but also in video games (e.g. the famous game *Minecraft* plunges its users into a highly pixelated universe in which many real buildings are reproduced) and the 3D representation of synthesis images. Finished element analysis methods also use these techniques of breaking down 3D space into voxels, for example, by analytically representing the dynamic behavior of physical phenomena (mechanical, thermodynamic, acoustic, etc.). The use of voxels as an architectural concept can also simplify the design of a building, while retaining a representative level of detail. We will now give a few examples of this.

3.3.1. *The evolving house*

In the 1940s, the Albert Farwell Bemis Foundation at MIT, provided for by the will of the well-known civil engineer Albert Bemis, coordinated a program on materials, methods and savings in construction, with the aim of developing the industry. In 1936, Bemis had published the third volume of his project The Evolving House [BEM 36]. The study explores questions associated with rationalized architectural design. The issues of prefabrication, mass production, construction industrialization and standardization of building components are explored. The modular design is central to his work, which presents the advantages of an elementary unit in the form of a cube. The cubical model became the main component (Figure 3.1) applied to a multitude of materials (wood, metal, cement, plastic) and to all building components (roofing, load-bearing walls, floors, linings, openings, staircases, etc.), and broken down for all constructive systems (wooden framework, metal, stonework structure, etc.).

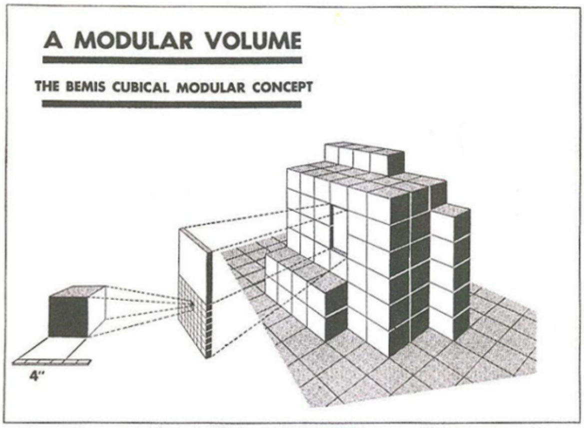

Figure 3.1. *Bemis's cubical modular concept [HOU 53]*

3.3.2. *VOxEL*

The VOxEL project was developed for a competition to create an architecture school in Stuttgart (Figure 3.2), by the architects Bollinger and Grohmann [BOL 10], in collaboration with LAVA (*Laboratory for Visionary Architecture*). They worked on a concept of spatial continuity and flexibility of spaces. The main structure is based on a 3D grid of voxels, each cell of which can be associated with two states: an "empty state" offering an open space and a "structural state" ensuring the structural qualities of the building based on the density of the bracing load-bearing walls. The composition of this cellular matrix has been genetically optimized to reach a structural optimum. The assessment criteria are based on the static behavior of the flooring under the effect of the vertical forces of gravity, on the behavior of the load-bearing walls under the effect of lateral stresses, and on the density of the walls, depending on the state properties of the cell. The configurations with the smallest torsional moment and the best compositions were selected and explored in more depth.

Figure 3.2. *LAVA VOxEL extension for the architectural school in Stuttgart, 2009. Three diagrams (left) show the generative principles: 1) attribution of functions; 2) cell stacking and 3) distribution of the program. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

3.3.3. *Other modular constructions*

Cubic architecture has long inspired many architects, such as Moshe Safdie, a pioneer of modular construction, who designed *Habitat 67*, a housing complex designed for the Montreal World's Fair, in the brutalist style. The aim was to combine the advantages of an individual home, built from adjustable prefabricated elements, with those of a high-density apartment block. To achieve this, Safdie [SAF 61] used the building design described in his thesis: in total, there are 354 units stacked up to form 148 apartments (Figure 3.3).

Figure 3.3. *"Habitat 67", modular architecture, brutalist style (Moshe Safdie). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

A similar concept, that of incremental architecture in an area where there is a shortage of affordable housing, is also built on a form of modular appropriation, such as in Weston Williamson's "*Palestinian housing*" project (Figure 3.4).

Figure 3.4. *"Palestinian housing" incremental architecture (Weston Williamson). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

Still with the aim of simplification, Grannadeiro [GRA 13] uses a grammar of parallelepipedal forms to generate architectones (as described by Kasimir Malevitch, a pioneer of suprematism). He developed a method to assist in the design of a building's geometric form (Figure 3.5), taking into account its influence on energy efficiency.

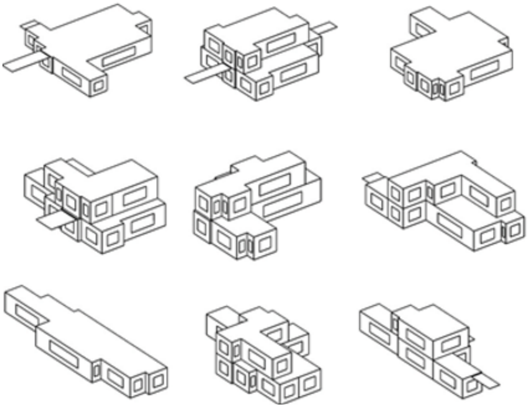

Figure 3.5. *Some of Grannadeiro's architectones*

3.4. Optimization through genetic algorithms

3.4.1. *Design and optimization*

Many problems relating to design or decision-making in building, particularly in the case of performative architectural or urban design, have been turned into programs combining combinatory generation and optimization phases. This combination is intended to greatly reduce the range of possible solutions and provide a sufficiently small number of good solutions for a practical study. There are many examples in the synthesis of forms [KIC 06] for multi-criteria decision-making support [RIV 13, ARM 15], or structural optimization [SAS 07].

As precise optimization is rarely used in the field of conceptual engineering (absence of any known mathematical or algorithmic solution, prohibitive calculation time), we resort to metaheuristics [HAO 14] based on stochastic algorithms. These are generic, usually bio-inspired methods: biology of evolution or animal behavior (genetic algorithms), algorithms of ant colonies (inspired by ethology), algorithms of swarms (inspired by the movements of groups of birds, fish and insects). Fairly quick and adaptable to a wide range of problems, these generative algorithms consist of building, assessing and developing the fitnesses of sets of solutions, in an iterative process that aims to explore the widest possible range of potential solutions, moving towards the best ones. They do not guarantee the optimality of the best solutions found, which we therefore refer to as *optimized*.

3.4.2. *Algorithms and evolutionary environments*

The “no free lunch” theorem [WOL 95] shows that, on average, there is no evolutionary algorithm better than another, if all possible optimization problems are considered. But, luckily, the optimizers are not all equivalent for a given set of problems. Success will therefore greatly depend on the suitability for the case in question, notably the adjustment of the parameters of the various stages of the algorithm, at risk of mediocre results. For example, adjustment of the three fundamental parameters – the number of solutions, selective pressure (section 3.4.3) and the probabilities of the intervention of variation operators (section 3.4.3) are far from trivial.

Introductory reviews of evolutionary methods can be consulted in [LE 07, DEB 11] or online[2], with mention of the researchers from whom we have borrowed some developments. These describe in detail the operational methods of the main families of algorithms, a description of which does not fall within the scope of this book: evolutionary programming, evolutionary strategies [REC 72], genetic algorithms, genetic programming [KOZ 94], distribution-estimating algorithms [LAR 01] and differential evolution algorithms [NER 09].

An evolutionary environment is composed mainly of three specific drivers: a generative driver (in architecture, we speak of a driver of morphogenesis), a driver of efficiency assessment (or criteria) and an evolutionary driver. It is the interaction of these three components that makes up the evolutionary mechanism. The assessment of each individual of the population in each generation can be manifold, for example, in an eco-generation perspective, in which it is principally environmental and energy criteria that guide evolution. Subjective criteria, notably associated with the interaction of the designer, are sometimes included in this list. We will come back to this later.

3.4.3. *General plan of a genetic algorithm (GA)*

Genetic algorithms are based on a bio-inspired formalism and the mechanism of natural selection in biological evolution (artificial Darwinism). *Phenotype* refers to the spatio-temporal structure (final form) that emerges, in a given environment, from the interpretation of the *genotype* (parameters or genes stored in chromosomes). Genetic patterns with great creative potential are called *pleiotropic*: this term denotes the interdependence of certain genes, leading to complex, often nonlinear dynamics, unable to foresee the evolutions or results of a minimum change.

Within a population (made up of buildings in this case), whose genes represent, for example, the spatial distribution of program elements or the properties of the envelope, the Darwinian principles of natural selection and random variation are implemented in an *evolutionary loop* to find a convergence towards the most efficient solutions (algorithm described in Figure 3.6).

2 www.aria.archi.fr/wp-content/uploads/2014/11/Rapport-final-EcCoGen.pdf.

– by means of a random uniform draw, we initialize the first population, whose individuals are assessed according to the chosen criteria;

– then, within the evolutionary loop, we construct and assess the generation (i), based on the preceding one (i–1). The selection stage favors individuals that optimize efficiency, while the variations applied to genetic heritage (Figure 3.7) create new, possibly more efficient individuals, taking into account their reproductive advantages. A final replacement step enables the best adapted individuals to survive, while the others disappear forever;

– finally, evolution ends when: either the desired efficiency level is achieved, or after stagnation (a significant number of generations without sufficient improvement of better individuals).

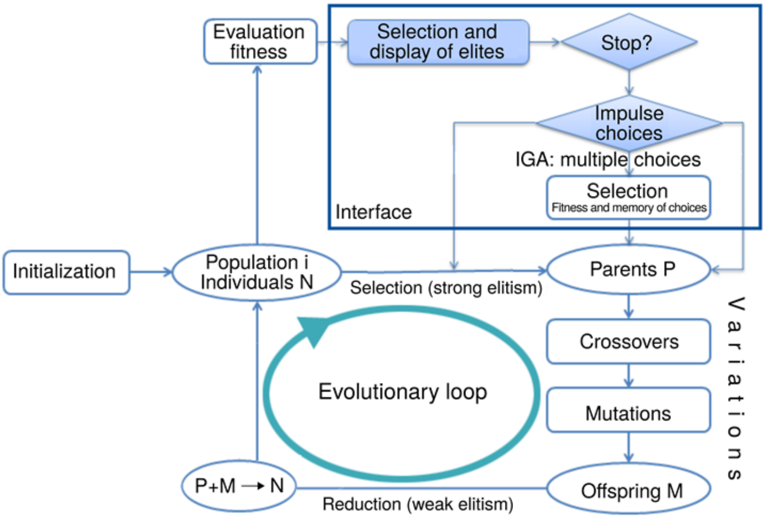

Figure 3.6. *Simplified plan of an interactive genetic algorithm*

We will now give a few additional details. Selection and replacement depend only on the efficiency of individuals and usually require two types of procedure: either random draw (giving each individual a probability of being selected in proportion to its efficiency), or deterministic tournament, making it possible to adjust the selective pressure. This pressure (higher probability of using the most efficient rather than the weakest) is set by means of a T parameter defining the number of comparisons through uniform draw of T individuals within the population, and retaining the best.

The principle of crossover is the exchange of genes or groups of genes between parents. According to this principle, high efficiencies are due to useful parts of the genome being transmitted to offspring, and mixing can result in combinations that increase efficiency. The principle of mutations (including swapping) uses stochastic processes to authorize partial alterations of the genotype, bringing about the emergence of new properties.

These operators are usually based on randomly chosen genes (uniformly along the chromosomes or in isolation). The most common working method is to sequentially apply a crossover operator, then a mutation or exchange operator, each with a given probability (respectively, p_c and p_m), authorizing fluctuations that generate diversity.

Figure 3.7. *Variation operators (crossover, mutation, swapping)*

3.4.4. *Pareto front*

Although it may seem right to the architect working with bioclimatic design principles, it is not theoretically correct to produce an optimization in two stages: for example, first the form and its orientation, then the characteristics of the envelope (openings, walls, materials, etc.). Indeed, these two phases are generally combined: they manipulate the same geometric data from which the parameters evolve.

In a multi-criteria problem, we seek to optimize several objectives at once, some of which may be contradictory. Many multi-objective evolutionary algorithms have been elaborated over the last two decades. Nonetheless, most of them have a shared characteristic: they manipulate a “Pareto front”, which denotes all non-dominated solutions, that is, those that are at least as good as all the others across all the objectives, and better on at least one objective [3.2]. In other words, we cannot improve the fitness of one solution of this front without damaging at least one other. These solutions therefore cannot be compared.

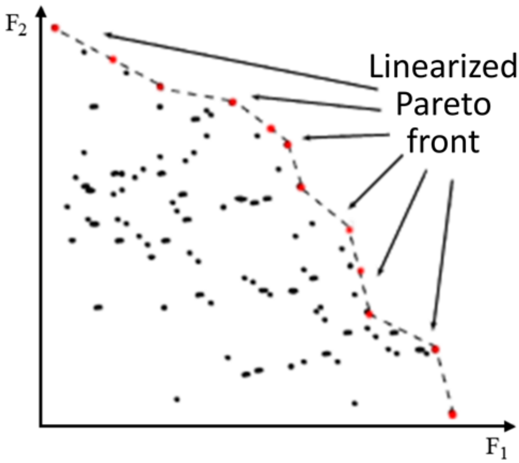

Figure 3.8. *Pareto front of a maximization problem with two objectives*

Mathematically, $(f_1,\ldots,f_n)$ are the fitnesses that we seek to maximize in the research area, and x and y are two solutions. We say that "x dominates y in the Pareto sense", which we call $x \succ y$ if:

$$\forall i \in [1,n],\ f_i(x) \geq f_i(y) \text{ and } \exists j \in [1,n] \ /\ f_j(x) > f_j(y) \qquad [3.2]$$

Figure 3.8 shows an example of a Pareto front for a problem with two objectives: the solutions are represented by points in the fitness area, and the extreme points (in red) for the dominance relationship [3.2] form the Pareto front of the problem. Note that the latter may be discontinued and have concave areas. It is often linearized (dotted curve).

As the solutions of the Pareto front are not comparable with each other in the sense of [3.2], they are the best possible compromises. In the end, it is always up to the user to make choices, bringing other criteria into play.

3.4.5. *Choice of fitnesses*

The choice of fitnesses is fundamental, because a problem can be incorrectly framed if just a few criteria are neglected: this is far more important for an architect than the optimization method used to solve it. Indeed, they effect a filtering in the space of possible architectural forms. As in most simulations, we can only know that the problem is correctly framed once we have solved it.

Furthermore, it is highly advisable to limit the number of fitnesses, because the size of the Pareto front tends to increase exponentially with this number [DEB 07]. Optimization problems are therefore generally easier to understand when there are not too many objectives.

3.4.6. *Multi-genomic algorithms*

An alternative approach for optimizing the form of buildings has been elaborated by the *Laboratoire Génie Civil et Bâtiment* (Civil Engineering and Building Laboratory) of ENTPE (France's National School of State Public Works) [NGO 14]. Based on multi-genomic algorithms – an extension of genetic algorithms – this approach enables the designing of non-standard forms by reducing the calculation time. A building is defined here as a 3D object formed from triangles, of which the sometimes numerous decision variables are the coordinates of the vertices. However, this approach makes it difficult to solve problems through conventional optimization methods, in which the number of variables must be limited. Multi-genomic algorithms make it possible to partly circumvent this difficulty, by refining the 3D model iteratively during the optimization process, through triangulation, introducing new decision-making variables at the crucial moment.

3.5. Detailed presentation of a genetic algorithm

This section describes in more detail the various components of a specific algorithm: the one established for EcoGen, which adapted to a relatively slow evolution that promotes the diversified exploration of a range of possibilities. The reader will thus be better equipped to understand the problems the researcher faces in solving the difficulties inherent in this kind of evolutionary mechanism, particularly in an environment of creativity stimulation.

3.5.1. *Jaszkiewicz's MOGLS*

The original algorithm (Multi-objective Genetic Local Search) was created by Ishibuchi [ISH 96]. It is a method for estimating the Pareto front (PF), the aim of which is to find a set of good solutions by using a single score, randomly combining the N fitnesses f_i. At each iteration, after a selection stage, a new solution is found through crossover, and then improved through a local search method according to the ongoing "scalarizing function": a norm that consists of optimizing a weighted sum of criteria [3.3], whose weight $\{\lambda\}$ is drawn randomly at each iteration [3.5]. A sign is given to each λ_i, indicating that the associated criterion is being maximized or minimized. The new solution therefore replaces the less effective solution in the population,

$$\|f\| = \sum_i \lambda_i \cdot f_i \text{ with } \sum_i \lambda_i = 1 \qquad [3.3]$$

In 2001, Jaszkiewicz showed that the MOGLS algorithm, based on a linear aggregation of criteria, makes it possible to access only the convex areas of the Pareto front. In 2002, he proposed a more effective version, in which the weighted sum [3.3] is replaced by *Tchebycheff's scalarizing functions* [3.4], which are better suited than linear functions. They make it possible to access the concave areas of the PF, when this is not convex [JAS 02]. The EcoGen evolutionary driver uses these functions, in a version adapted to maximize fitnesses [3.4],

$$\|f\| = \min_i (\lambda_i \cdot f_i) \qquad [3.4]$$

In [CAR 08], the author observes that in this class of hybrid algorithms, the genetic part, deprived of mutation, has an exploratory role, while local research, devoted to the intensification of research, has a very long calculation time. This means that we can initially choose not to implement it, especially when extreme optimization is not the most important aim of an IGA. Instead, he shows that an *evolution strategy* operation $(\mu + \lambda)$-ES produces MOGLS with excellent results, more quickly. Remember that, in this type of strategy [REC 72], the population of μ parents + λ offspring is reduced to μ individuals at each iteration, who become parents in their turn.

The use of Tchebycheff functions promotes the search for diversified solutions, as {λ} coefficients are randomly generated by the algorithm [3.5], in an area of $[0, 1]^n$, *X* being a random variable between 0 and 1,

$$\lambda_1 = 1 - \sqrt[N-1]{X}\,;\ \lambda_k = \left(1 - \sqrt[N-1-k]{X}\right).\left(1 - \sum_{i=1}^{k-1} \lambda_i\right);\ \lambda_N = 1 - \sum_{i=1}^{N-1} \lambda_i \qquad [3.5]$$

In practice, we systematically assess the "standard" fitnesses between 0 and 1, to escape the possible impact of the differences in amplitude. Thus, at each iteration, we estimate the lower and upper bounds of each *fi* efficiency, making it possible to define the Tchebycheff norm for a maximization problem [3.6]. In what follows, we will look for the maximum of this norm.

$$\|f\|_\lambda = \min_i(\lambda_i \cdot \overline{f_i});\overline{f_i} = \frac{f_i - \min(f_i)}{\max(f_i) - \min(f_i)} \qquad [3.6]$$

3.5.2. *Directional optimization*

In [ISH 02], the authors propose an improvement of the MOGLS, using an optimization direction suited to each solution in the "local research" phase, making it possible to combine genetic evolution and exploration of the neighborhood. Even if we do not use "local research" (e.g. to speed things up), this directional optimization method can be used to direct the research effort into an interactive mode, once the user has specified their preferences [CAR 08]. It is sufficient to work out the {λ′} coefficients of *Tchebycheff's induced norm*, which optimizes the ranking of f_i criteria associated with a solution marked by the user [3.7],

$$\lambda'_k = \frac{\prod_{j\neq k} f_j}{\sum_{i=1}^{N} \prod_{j\neq i} f_j} \qquad [3.7]$$

The MOGLS algorithm is then used as a series of single-objective optimizations, blocking the {λ′} values for the following iterations with each new choice. If the user makes several choices, we obtain a sample of the preferences space, from which it is necessary to construct a distribution of substitution with uniform repetition $[0, 1]^n$ in the native algorithm. Note that this pattern lends itself very well to the use of the excellent MOEA-D algorithm [ZHA 07], which is currently being tested.

3.5.3. *Maintaining population diversity*

Preserving diversity is essential to prevent all the individuals in a given population from being trapped in local minima (single-criterion research), or *turning* towards a specific area of the Pareto front (in multi-criteria research), a natural tendency of evolutionary algorithms [GOL 89]. An additional objective is to guarantee the uniform distribution of solutions along the Pareto front. To ensure this diversity, we can take action:

– *Upstream*: by encouraging convergence towards the Pareto front (or global maximum), while maintaining the diversity of the population in the criteria space or on the genetic level. Here, we can note that MOGLS is designed to promote initial diversity (because it uses a new weighting of objectives with each iteration), while ACROMUSE (section 3.5.4) promotes subsequent diversity. We will certainly gain in efficacy (convergence time and solution diversity) by replacing the MOGLS algorithm with an adapted version of the MOEA-D algorithm [ZHA 07, LI 09, LIU 13], which promotes parallel convergence of multiple small populations towards diversified areas of the PF. Furthermore, it is suited to processing more numerous fitnesses and has a high degree of genericity.

– *Downstream*: we use measurements of local population density in the criteria space to promote the exploration of the less populated areas. A very good solution for measuring local density, which does not require much calculation time, is the PADE (Population Size Adaptive Density Estimation) method. It requires no empirical parameter and can therefore, in theory, adapt to any type of problem [ELA 07]. PADE is used to reduce the size of the population as soon as it exceeds a threshold value that is fixed from the start. To achieve this, it divides the criteria space according to the hypergrid, whose dimensions and number of cells depend on the size of the standard population. Used alongside MOGLS, PADE iteratively removes individuals of maximum local density and lesser efficiency according to the ongoing *scalarizing function* (Figure 3.9).

3.5.4. *ACROMUSE*

Adaptive Cross-over Mutation and Selection (ACROMUSE) is a single-objective genetic algorithm [MCG 11]. Its main purpose is to maintain a population of individuals that is both diversified and efficient. Thus, ACROMUSE prevents the population from converging uniformly towards a single solution. The other elements of the population also evolve, but maintain a degree of diversity. We therefore obtain other local extrema, which can be highly useful for assisting in designing.

Its second point of interest lies in its ability to adapt to rapid changes in the research landscape, through dynamic adjustment of crossover, mutation and selective pressure rates, based on statistical analysis of the standard population. For this, the reproduction basin is divided into two populations of individuals: those who undergo a crossover and minor mutations, and those who undergo only major mutations (Figure 3.9). A measure of the genetic diversity of the population (*SPD*) is used to adapt the crossover and strong mutation rates, while selective pressure is controlled by another measure combining genetic diversity and efficiency (*HPD*). The mutation rate is also adapted to each individual through recognition of its efficiency (the lower it is, the more likely the individual is to mutate). Individuals are selected depending on their *hpd* contribution, measured by *HPD*, rather than on their pure efficiency. ACROMUSE therefore produces a very good balance between exploration and exploitation, but its original version requires the adjustment of three parameters: the maximum *SDP* and *HPD* values (*SPD_max*, *HPD_max*) and selective pressure $T = |P|/k$ (k is fixed at 6 by the authors, but is adjusted more precisely, as will be explained later on).

3.5.5. *Improvements and multi-objective extension*

In 2013, we showed that measurements (*SPD*, *HPD*) must be performed on the total population before the reduction stage [MAR 13a], which McGinley [MCG 11] had not realized. We also observed that it is preferable to use dynamic values of *SPD_max* and *HPD_max*, updated at each iteration and depending on the maximum values recorded during the session. These two improvements lead to faster convergence towards the local optimals (or the Pareto front, in a multi-criteria framework).

We then developed a hybrid MOGLS and ACROMUSE algorithm, extending the latter to multi-objective processing. In fact, the 2011 version of ACROMUSE is designed only in a single-objective framework, which greatly limits its use. To use it with several objectives, we naturally replaced its unique fitness with the scalarizing function of [3.6], by means of some adjustments described in [MAR 13a]. We obtained excellent results, at the cost of a slight increase in convergence time.

3.5.6. *Use of GA as a constraint solver*

The application of variation operators hardly ever results in consistency (respect of constraints): consistent parents rarely have consistent offspring. To resolve this defect, we can use repair mechanisms (which take a long time and damage evolutionary capacities), *ad hoc* genetic operators that guarantee the consistency of the solutions produced, but lose their efficacy when the number of constraints increases, or even easing the constraints, which involves setting a tolerance on which we can act. Another solution consists of transforming certain constraints into objectives, which increases the complexity in terms of calculations and the size of the PF, and encourages the emergence of random or pointless solutions.

Better results are obtained when a certain degree of inconsistency is tolerated in the solutions, which has the effect of not disturbing the evolution too much. We often manage to decrease the inconsistency rate in this way by introducing a *z* function of efficiency penalties. An elegant and effective way of dealing with this problem is to integrate the notion of consistency into the dominance relationship [DEB 02b], effecting selection tournaments based either on efficiency or on the minimization of inconsistency:

$$x \leq y \Leftrightarrow (z(x) \leq z(y) \text{ or } (z(x) = z(y) \text{ and } x < y)) \qquad [3.8]$$

Another method makes it possible to redefine the dominance relationship by means of constraint-dominance [COE 02, COE 07]. With MOGLS, as we do not directly use the dominance function, we use the standard *scalarizing function f(x)* to penalize fitness [3.9] during the selection step (in maximization):

$$f_z(x) = f(x) \text{ if } z(x) = 0, min(f) - z(x) \text{ otherwise} \qquad [3.9]$$

3.6. Interactive evolutionary algorithms (IEA)

3.6.1. *Possibilities and limitations*

With IEAs, the user can interact with populations and intervene in the evolutionary loop, particularly in the initialization, selection and mutation stages, to subjectively guide evolution [LUT 05]. The usual applications involve musical creation, image synthesis, data mining and e-learning, and often integrate objectives relating to subjective judgments or sensory impressions.

Local interventions directly on the genotypical level (the coded solution) or phenotypical level (the generated solution) may be envisaged. An interaction on the phenotypical level can be very useful in a creative context, from the moment when it is possible for the user to have an idea of the partial components of the ideal solution (section 6.2.1 in Chapter 6).

Interaction encounters a certain number of limitations, however:

– Slowness of the process associated with recognition time, limited population size and simplification of the assessment required to preserve an interaction in real time.

– Apathy of the designer in the face of a large number of choices and generations. To prevent repetitive interactions, we have to vary their modalities and develop effective interrogation mechanisms (e.g. a phase of implicit learning from choices).

– Difficulty of finding a compromise between pure optimization and maintenance of priority interest areas in the research landscape.

– Difficulty of following the choices of the user, ensuring them a degree of longevity, neither too short (to give the GA time to take them into account), nor too long (to not hinder exploration of other potentially interesting areas). Quiroz *et al.* [QUI 08] describe an IGA (Interactive Genetic Algorithm) in cooperative mode, based on the most commonly used genetic algorithm: NSGA-II [DEB 02a]. The main point of their work is the construction at each iteration of a virtual interpolated fitness to guide the IGA towards the (unique) choice of the user. Other solutions are assessed based on the similarities with this choice, but this virtual fitness is therefore no longer able to take into account the objective quality of a solution.

– The problem becomes yet more complicated when what we want to optimize is not mathematically assessable or measurable (e.g. the simple notion of satisfaction or desirability [PAI 11]).

3.6.2. *Multi-objective optimization combined with an IGA*

In multi-objective optimization, we seek a reasonable approximation of the Pareto front (generally unknown). Moreover, in interactive mode, the problem lies in finding solutions that satisfy the user's requirements as far as possible [KAT 13]. We often assume that these solutions must be found somewhere on the Pareto front because we believe, from a quantitative point of view, that the user must prefer a non-dominated solution to a dominated one. But this is debatable if we bring in other points of view.

Then, to limit fatigue, we must promote quick and diversified convergence to the Pareto front, which is often contradictory [LLO 05, QUI 09]. On the other hand, however, in order not to shatter the ongoing optimization dynamic by taking into account the successive choices of the user, we must try to build operators that slowly and fairly constantly distort the standard object (μ=kλ strategy, few mutations and crossovers, more local than uniform). This is what Carpentier explains in his thesis [CAR 08], in which he sets out a very interesting method for directing a joint effort to find and optimize solutions when the user has input his preferences.

Finally, one question is often raised about IEAs: are we obliged to involve the user in the evolutionary loop? Is it not enough to give him a complete Pareto front created from the convergence of a large number of *runs* and to then guide him in his choices? Beyond the fact that the complete Pareto front can take a long time to obtain, the involvement of the architect in the form genesis process is fundamental. Working only from the optimal result, we would neglect the non-optimized niches in which the user might have lingered. Thus, in [QUI 08], the IGA makes it possible to retain objectively inferior solutions if they are amplified by repeated user choices, which puts into perspective the efficiency-based score. We therefore avoid methods that require a lot of calculation time (e.g. local research), in favor of focusing more on diversity. In this sense, the evolutionary path can be as important as the final result.

3.6.3. *A multi-objective IGA for efficient and diversified solutions*

EcoGen's genetic algorithm includes five modules: MOGLS-(μ+λ) with μ=2λ as an evolution strategy and a dynamic adjustment of population size |P|, the multi-objective extension of ACROMUSE, a constraint solver, the PADE reduction procedure and the pheromonal IGA (Figure 3.9). The MOGLS-based method is inspired by its use in Carpentier's thesis [CAR 08]. Simpler to use than the NSGA-II-based method of [QUI 08], it allows for a natural implementation of ACROMUSE, the unique fitness of which is replaced by a scalarizing function. Furthermore, it offers more flexibility for truly directing a research effort based on user choices in the interactive mode.

3.6.3.1. *Genome structure*

We have opted for a linear (and therefore non-pleiotropic) description of the genes associated with the positions of voxels in the "capable volume" (CV). This kind of structure preserves "genetic patterns" and "topological consistency" when variation operators are applied. This means that crossovers and mutations occur in the same places along the chromosomes, and we always remain inside the CV.

3.6.3.2. *Constraints*

An initial programmatic constraint concerns the specification of the surface area to be built on, with a possible tolerance. To resolve it, we define the *z* function of penalization as the gap between the imposed surface area and its measured value for a solution. The other programmatic constraint relates to the distribution of usage types: this is also resolved using the same technique.

3.6.3.3. *Selection*

Although binary tournament selection (T=2) is most efficient for Jaszkiewicz's MOGLS [JAS 02], the same cannot be said for the MOGLS-(μ+λ)–ACROMUSE hybridization approach. We have carried out numerous tests to fine-tune the k parameter of selective pressure T=|P|/k, and ultimately obtained the value 9.5. To build the reproduction basin, T individuals are always drawn at random from the standard population, with reduction (but the best is chosen based on its *hpd* contribution), and the operation is performed (2λ) times.

3.6.3.4. *Crossovers and mutations*

Crossover and mutation operators are then applied to the reproduction basin candidates (in pairs), and the new individuals are integrated into the standard population. As the ACROMUSE mechanism is based on genetic diversity, it can be applied independently and differently to genes of different kinds. We obtained very good results with uniform crossover (random inversion of genes from the parent chromosomes, in place and area, permitted by topological consistency), multipoint mutation and a swap operator, with the same application rates as ACROMUSE.

3.6.3.5. *Replacement*

The replacement stage, which is based on that described in [CAR 08], uses the PADE algorithm. However, removal is performed by eliminating an individual with a lower contribution to the *hpd* index in a case of maximum grid density, instead of the standard scalarizing function. We begin by applying PADE to the Pareto front only if its size exceeds a threshold currently fixed at 40% of |P|. The non-Pareto population is then considered. Either we iteratively remove the least consistent solutions, until we return to the desired population size, or the number of solutions with minimum consistency always exceeds the size limit, and the population is reduced by PADE.

3.6.3.6. *Interactivity*

> *"How can the sensitivity and esthetics of the author be integrated into a program that is currently managing measurable data? We will answer this question with caution, given that we must not seek a perfect solution, but make compromises and find the right balance between elevated properties and an interesting form, disposition and aspect. This caution in the face of digital tools is part and parcel of science, but is also necessary in order to avoid falling into the trap of letting machines dictate our design methods. An important instinct is to get some distance from the generated solutions, sort them, compare them and select them so that the retained components are as close as possible to our expectations, as much in terms of efficiency as of form"* (Benjamin Gevers, architect).

As the morphological criterion is fundamental for an architect, we use it together with fitnesses to mark the prioritized forms in the landscape of proposed solutions. This can be done simply by equipping the stochastic area of choices with pheromonal markers $M(\lambda)$. Remember that, in nature, ants move and orient themselves by means of pheromones, which are volatile olfactory substances that act as a collective memory. This concept forms the basis of the ACO (Ant Colony Optimization) metaheuristic, used mainly in combinatorial optimization, using traces of pheromones to mark the components that promote the best solutions [ALA 07, ANG 09].

Thus, when a solution is chosen by the user, we store it with its "induced λ" [3.7] and its form in a distribution space, E. We define a *Resemblance(λ)* function that compares the occupancy indices of a solution (in the capable volume) with those of the form associated with λ. The *overall resemblance* is merely the sum on E of the product of *M(λ)* and *Resemblance(λ)*.

At each iteration of the IGA, a single pair (λ, form) is selected in E by means of random stochastic sorting based on markers, M. We then let the algorithm pursue the standard iteration, but modify the selection stage: 90% are selected on global resemblance, and 10% on *hpd*. This effective duration mechanism facilitates consideration of the subjective choices and their consolidation over the generations. The pheromonal reward is based on the repetition of choices in E, rather than on efficiency (of which weighting λ is already taken into account). It takes place at the end of each iteration, following which the markers, M, are updated through the evaporation mechanism [3.10], whose rate has been adjusted to the value 0.01:

$$M = M(1 - \varepsilon) \qquad [3.10]$$

This mechanism makes it possible to reinforce the user's repeated choices and decrease the influence of former choices. If we are not in interactive mode, M markers are not taken into account, and undergo only temporal evaporation.

3.6.3.7. *Note: another possibility for GA/ACO hybridization*

First, remember that in the classic pattern of the ACO metaheuristic [SOL 10], a heuristic function expresses the interest of choosing an element for itself, without reference to a construction history, while the pheromone expresses this interest in comparison to other components, taking into account the history of choices. Using ACO, we could associate a pheromone trace and heuristic function with each objective, in order to attempt to optimize it independently from the others [ANG 09]. During the construction stage, we would successively add the most attractive component (produced from the heuristic by the pheromone). These components could be positions in the capable volume in the framework of formal constraint resolution, and the heuristic could be used, for example, to indicate a form preference.

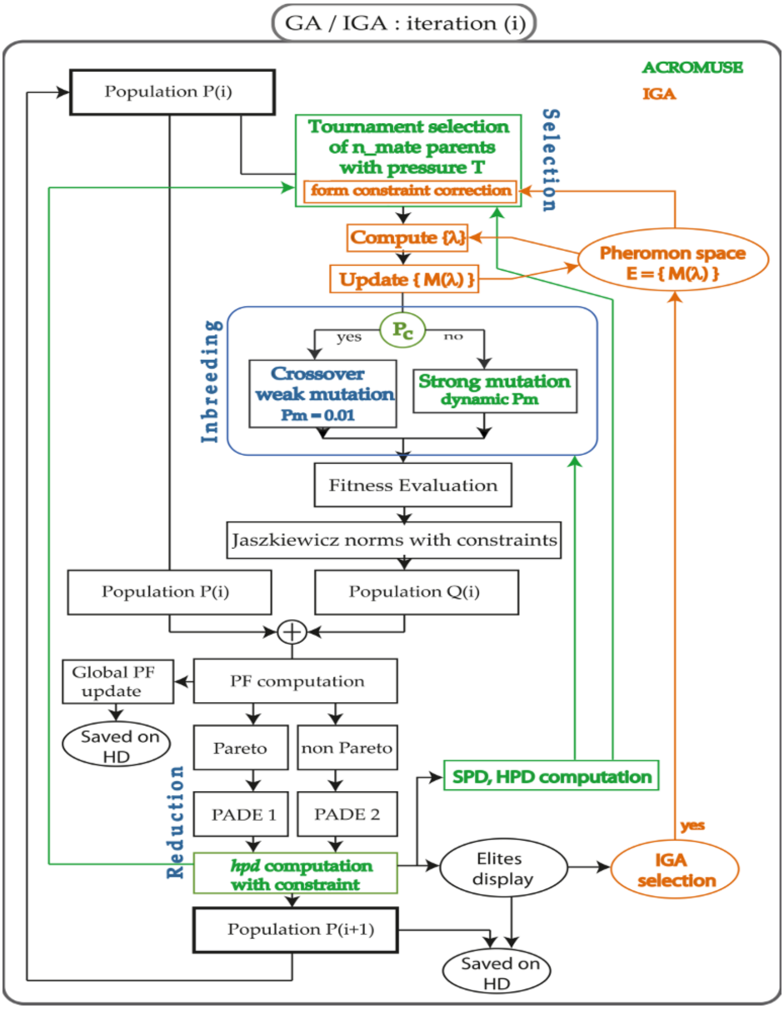

Figure 3.9. *Organizational chart of an iteration of EcoGen2's genetic algorithm. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

4

Assessment Models and Meta-models

> "*All models are wrong, but some are useful!*" (George Box, mathematician, [BOX 76])

The aim of this chapter is not to describe all the assessment models and tools relating to building efficiency, but to show, based on examples, that the various stages of architectural design (early and advanced) involve different models and different tools. As the saying goes: "*the right tool at the right time*". This separation notably requires various descriptions (logical, hierarchical, physical, geometrical, systemic) of the objects used, along with the assessment models adapted to suit them.

Simplified modeling – which mainly involves assessing efficiencies in the upstream design phases – remains a highly valuable tool, even in an age of increasingly fast computers. Simplified representations can be obtained from precise physical/digital models through approximation techniques (often statistical) or reduction using meta-models.

4.1. The concept of a model

A model is always a simplified representation of reality, and its quality depends on the knowledge and techniques available for understanding and describing this reality. Models are used to understand, explain, design, predict and decide. Some researchers think that a relatively incorrect model is better than no model at all; this is true, for example, for life cycle analysis (2.3). And a comprehension model, even an approximate one, is preferable to no model. However, if its purpose is to predict a phenomenon, what is the

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

point of a model that produces results that differ greatly from reality, especially if it is used to support decision-making?

For a scientist, modeling a system or phenomenon can involve several phases: suggesting hypotheses, producing a pattern of interactions between its components, describing it using a mathematical and/or algorithmic formula and creating a prototype to reproduce it through simulation. Modeling using mathematical and/or digital tools has six important stages: data acquisition, calibration, simulation, sensitivity analysis, validation and interpretation of results.

In architecture and engineering, the term *model* is used in various contexts: a mock-up (physical or digital), a plan acting as a prototype, a conceptual system designed to support understanding and diagnostics, an analytical or algorithmic representation of phenomena and their relationships, or simulation models (analytical, statistical, stochastic, etc.).

There are several types of modeling: imperative, declarative, generative and meta-modeling. In imperative modeling, the designer must precisely define all the characteristics of the objects that make up the scene or environment, which, in order to be credible, must be abundant enough and often long enough to model. Declarative modeling – also called *reverse simulation* – enables forms and spaces to be designed from vague or imprecise descriptions, or simply from a set of properties (morphological, structural, operational) or objectives to achieve [GAI 03]. Often used in architectural research, it makes it possible to obtain an iterative approximation of models, which will then be refined, for example, with a constraint solver combined with an optimization engine. The broader concept of meta-modeling refers to establishing principles, rules or formalisms, according to which the model itself is generally designed, but from which it can also emerge.

4.2. Models and tools suited to the advanced phases of building design

The term *environment* – denoting an area with uniform atmospheric qualities, characterized by a minimum surface area, its proportions, a volume, atmospheric characteristics with an acceptable variability depending on use, and any other property that can be used in the detailed assessment model – is fairly appropriate for an architect. The same can be said for dynamic energy efficiency simulations (thermal, lighting, acoustics, ventilation) based on zonal modeling. Especially in the sketching phase, manipulating spaces (themselves broken down into sub-spaces, centers and volumes) seems more intuitive to an architect who draws their boundaries in terms of lines or surface areas. Ideally, we would be able to use the two approaches simultaneously, but models based on outer surface areas are generally easier to develop and, particularly, to use in the upstream phase.

4.2.1. *Detailed modeling of the energy behavior of a building*

The behavior of a building is influenced by numerous factors, such as the use of the constituent materials and their thermal properties, lighting, HVAC (heating, ventilation, air conditioning) systems, weather conditions, occupancy rate and user behavior. In this context of precise and detailed calculations, Clarke has produced a detailed overview of the processes required to build a detailed model of thermal transfer in a structure [CLA 01]. Regarding HVAC systems in particular, a detailed energy calculation is provided in [MCQ 05]. Also see [BON 15] for in-depth analyses of thermal, aeraulic and lighting models.

The efficiencies of structures can be precisely assessed using reference software programs, such as TrNsys[1], EnergyPlus[2], BLAST[3], IES-VE[4], Pléiades/COMFIE[5], DOE2[6], and ESP-r[7], developed to assess their efficacy and sustainability and enable them to be energy dimensioned. A fairly exhaustive list of 453 energy simulation software programs can be found on the site[8].

Generally, although these simulation tools are effective and precise, based as they are on physical principles, the vast majority of them require input data (construction details, technical mechanisms, materials, environmental parameters) that are not readily available in the sketching

1 www.trnsys.com.
2 www.energyplus.net.
3 www.wbdg.org/tools/blast.php.
4 www.iesve.com.
5 www.izuba.fr/logiciel/pleiadescomfie.
6 www.doe2.com.
7 www.esru.strath.ac.uk/Programs/ESP-r.htm.
8 www.buildingenergysoftwaretools.com.

phase. Therefore, they cannot be used in the upstream design phase. For example, control of aeraulics in the upstream phase is almost impossible, and still more so in an interactive computing way. It requires sufficiently detailed knowledge of the geometry, openings, passive and active equipment and conditions of use. It is the object of dynamic thermal simulations, carried out using TrNsys, EnergyPlus and IES-VE, and requires often lengthy calculation periods (from a few dozen seconds to several hours) for a solution.

4.2.2. *Thermal regulations in France*

RT2012, the thermal regulation in force in France in 2017, was originally based on the efficiencies of the BBC (low-energy building) label. Calculation software programs are recommended for estimating three efficiency indices according to the detailed Th-BCE 2012 calculation method established by CSTB [RÉG 12], which is not highly suited to the project's sketching phases. It involves indices: Bbio (to assess a building's intrinsic thermal qualities, independently from its heating systems), CEP (which assesses primary energy consumption using energy-efficient equipment in order not to exceed a threshold of 50 kWhep/m^2/year in a private home) and TIC (conventional internal temperature, related to passive summer comfort). An effective Bbio (the most accessible parameter for calculation in the upstream phase) is obtained by optimizing the bioclimatic design of the building, i.e.: (1) arranging the orientation and layout of openings to promote solar gains in winter and reduce them in summer; (2) prioritizing natural lighting (especially for the October–March period in Europe); (3) reducing thermal loss; (4) taking into account inertia for summer comfort.

4.2.3. *Software environments for project simulation*

In the fields of building, architecture and urban planning, multi-efficiency simulation software programs have existed for more than 20 years. They develop alongside the models and regularly improve their calculation capacities, benefiting from the progress made possible by equipment and computing systems. The calculations are certainly increasingly precise, but they still often take a long time to perform, especially when hundreds or even thousands of cases are being assessed, as is the case for optimization. We will briefly present a few simulation platforms that are frequently used in the architectural design phase and in design offices. Most of them have been or are still being developed in connection with research teams.

4.2.3.1. *SOLENE*

SOLENE is a set of urban microclimate simulation software tools (radiative, thermal, aeraulic assessments, etc.) developed since the 1990s at the CRENAU laboratory[9]. Initially designed to calculate sunshine, lighting and thermal radiation for architectural and urban projects, the SOLENE platform now makes it possible to simulate the influence of various urban planning decisions on the scale of a neighborhood on surface temperatures, outdoor comfort, energy consumption of buildings, attenuation of the urban heat island effect and transformation of urban places and landscapes (analysis of visibilities). It takes into account the interreflections between buildings and calculates a *long-wave* radiation assessment for each surface (infrared flows emitted and received by the building facades, exchanges with the sky and ground). Finally, use alongside SOLENE-micro-climat [MOR 15] supplements the program with urban aeraulic calculations.

4.2.3.2. *Pleiades+COMFIE*

Pleiades is a complete building design and energy and environmental assessment software program developed by Izuba Energies. The Alcyone graphical modeler allows for fast entry of the building's envelope, its thermal properties, masks, systems and usage information. The thermal calculation is based on the COMFIE engine developed by the "*Centre Efficacité énergétique des Systèmes*" ("Center for Systems Energy Efficacy") at the Paris Ecole des Mines. The natural light calculation is based on the Radiance software. Systems modeling is carried out according to the Th-BCE 2012 regulations, with the exception of the air-handling units, which are not modeled.

4.2.3.3. *EnergyPlus*

This tool enables energy simulations to be carried out for one or several buildings. Unlike SOLENE, multi-building calculations must be launched simultaneously. For example, its Python language interface facilitates its association with multi-objective optimization methods on the scale of a block, or sensitivity analyses.

9 www.aau.archi.fr/crenau.

4.2.3.4. *MIT Design Advisor and ArchiWIZARD*

These two tools are designed to keep the user informed during the design phase. MIT Design Advisor[10], an online tool developed by a team at the MIT Department of Architecture, makes it possible to produce a thermal analysis very early in the project process, using internal contributions within the building. It is a tool designed for architects, and it is simple to learn. It makes it possible to obtain indications as to the efficiency of the envelope at the very beginning of the design process. Thermal assessment is based on physical characteristics (orientation, composition of walls) and usage of space.

ArchiWIZARD[11] is a design support software program based on various European standards and using the current calculation methods of the thermal regulations. It is also used in the first stages of design to verify the energy-related challenges of the project as early as possible, but it can be used until an advanced project definition report is produced. It produces a precise calculation of the solar gains through the *ray-tracing* method, taking into account direct solar gains and interreflections between the building and its immediate environment. Its most important role is to make it possible to import the geometry of the project or of an existing site from all the currently available formats and to carry out a thermal or lighting calculation very quickly.

4.2.3.5. *Ecotect*

This is a complete simulation program that connects a 3D modeler with solar, thermal, acoustic and economic analyses. Easily connected at the outlet to Radiance and EnergyPlus, Ecotect is used mainly in environmental design during the conceptual stages of the project.

4.2.3.6. *IES Virtual Environment*

IES-VE[12] is a highly professional and complete platform designed for building simulation, for engineers as well as architects (the program offers two entry levels). Benefiting from a large R&D team, it has an extended range of functions: dynamic thermal simulation, winter and summer thermal comfort assessment, reduction of the need for heating in winter, increase in

10 www.designadvisor.mit.edu/design.
11 www.graitec.com/fr/archiwizard.asp.
12 www.iesve.com.

summer thermal comfort, specific consumption needs (heating, ventilation, air conditioning, etc.), optimization and quantification of internal contributions, dimensioning of natural lighting depending on use, optimization of natural ventilation, thermal requirements assessment and bioclimatic optimization.

4.3. Simplified modeling: difficulties and examples

In the sketching phase, the designer works from vague data and imprecise problems. He is familiar with only one operation context (climate, urbanism constraints, form and quality of the urban context, schedule, expectations of the Contracting Authority). The spatial organization, the form and details of the structure, its precise dimensioning, its materiality and its constructive system are only rarely known in advance.

The data required for assessing the structure's efficiencies will emerge only in the first realizations, which justifies the fact that assessment models often work from statistical data. However, it is not frivolous to propose simplified building assessment tools, the obstacles and risks being numerous, especially in terms of the physical modeling aspect and questions relating to materials, systems and uses [ATT 12, JON 13]. Simplified or reduced-scale physical models must overcome three major constraints: adapting to the geometric scales of the morphological model, making do with the available data in the sketching phase, and assessing efficiency in short computing time.

4.3.1. *Geometric scales*

In the sketching phase, the geometric scales manipulated simultaneously by the designer go frequently from the urban scale (form, profile and sketch) of the block and the urban fragment to that of the architectonic detail linked to the materiality envisaged for the building (constructive system, appearance of the envelope, ornamentation). The sharpness of the geometric models should come down from the general sketch to the scale of the area or the spatio-functional unit. But more detailed scales may be required, depending on the model (for example, the scale of the solar protection device for assessing external energy contributions or risk of glare).

4.3.2. *Processing speed*

The sketching phase, in an operational situation, is brief. The project manager cannot, from an economical point of view, devote more than a few days to a few weeks (according to the scale of the project) to looking for solutions. A certain number of characters must be quickly stabilized, although they can be questioned in the downstream phases, in a cyclical movement of reverse design.

Furthermore, an evolutionary algorithm is pointless unless it works with a sufficiently large population of solutions so that diverse solutions can emerge. The calculations performed to produce interesting efficiency-based solutions may take a long time when the number of objectives is high (approximately several hundreds of iterations, depending on the number of parameters).

To ensure the maintenance of smooth interactivity (an essential parameter for the creative dimension of the mechanism), it is therefore crucial that physical models can provide approximate assessments in a very short time, preferably around a hundredth of a second or less (section 5.8 in Chapter 5). This is obtained using:

– optimized algorithms, for each assessed criterion (frequent technical obstacle);

– simplified modeling or meta-modeling;

– an architecture of optimized development, generally parallel.

4.3.3. *Simplified thermal modeling in winter or summer conditions*

To circumvent, among other things, the lengthy calculation times and without denying the complexity of built systems, for around 15 years, researchers have been proposing simpler alternative models, notably for assessing the thermal behavior of a building with quantifiable precision, or predicting its energy consumption in a given period. Among the simplified physical modeling methods adapted to thermal transfer in winter conditions, we might mention:

– adaptation of the unified degree-day method, which works only in a steady state, where a single score is used to assess the energy consumption of small-scale buildings where energy exchange across the envelope is dominant [ALH 01]. This method dates from the 1960s and consists of determining the sum of the positive gaps between an internal setpoint temperature (18°C) and a temperature representative of the day (outdoor climate over a given period – many climatic databases provide temperature information for various towns. It takes into account: heat losses in kW/h, losses from the building through the envelope and through ventilation. These losses are offset in part by taking into account solar gains and internal contributions. It is interesting because it requires only a few values to be viable. Furthermore, these values can be abstract;

– the refining of the degree-day method with the implementation of polynomial functions for predicting the energy efficiency of a dynamic composite envelope depending on the physical characteristics of the components of the envelope. The development of EcoGen1's energy consumption engine [MAR 13b] was based on this principle;

– the modification of the ASHRAE standard on the basis of a load factor method for a residential neighborhood, a simple method that can be manually calculated [BAR 05];

– the development of xRyC models [NAU 16], notably with frequency and amplitude responses, which can work in a dynamic regime, to model large buildings where the internally generated stresses are dominant and the loads are not linearly dependent on the external/internal temperature difference [ALH 01, VEL 15];

– inertia modeling, using a network of clustered thermal masses [WAN 06];

– modeling techniques to obtain thermal resistance profiles for composite walls;

– the development of regression models to predict the winter heating consumption of a building.

We will now give a few examples, based on similar principles, for the summer period:

– the design of simple models, based on a combination of the results of detailed simulations, in order to determine the cooling load of a building [YIK 01];

– the development of empirical models based on a comparative assessment between the real and standardized energy efficiency of a high-efficiency residential building fitted with a cooling system [DAL 12];

– the development of digital models for predicting the thermal behavior of buildings under the influence of all possible thermal loads and the choice of the cooling system, in connection with the thermal comfort requirements [TZI 11];

– approaches using bio-inspired algorithms: the development of modeling techniques based on a simplification of the physical characteristics of buildings through a frequency analysis and the simultaneous development of genetic algorithms to identify the parameters of the model depending on the operating data [WAN 06]; the development of neural networks that calculate long-term energy demand based on short-term predictions (generally 2–5 weeks) from the data measured [OLO 01, KAL 06, YOK 09].

4.3.4. *Solar gains received by the envelope of the buildings on a site*

The reader should be aware that a patent has been filed for some units of the EcoGen2 software program. In particular, the three bioclimatic fitnesses described in the following sections (and in Chapter 5) use an effective calculation method known as "*target-computing*", which is an important part of EcoGen2's "algorithmic heart". Neither its software implementation nor the details of how it works have yet been published. We will provide only a few useful summary points for elementary understanding.

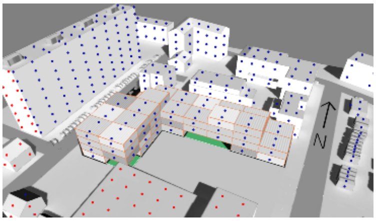

Figure 4.1. *Simplified example of division of the walls and roofs of a "building and project" set into targets (in red: those not involved in the calculation). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

Solar gains are assessed based on an irradiation calculation engine, automatic and scalable in the spatial and temporal dimensions. It is based on a simplified *ray-tracer* model with, among other things, division of the built space into targets (Figure 4.1).

4.3.5. *DaylightGen*

Gallas offers an approximate method that guides the designer through the project design phases to help him overcome the complexity of taking into account integration and control of luminous atmospheres [GAL 13]. It enables him to declare, to define his intentions in terms of luminous atmospheres (through a collection of images) and to realize them by proposing architectural configurations respecting these atmospheres. The DaylightGen tool will then determine the concepts that characterize the effects of light affecting the designer to generate the architectural solutions that illustrate these intentions. For this, it uses the optimization algorithm *Galapagos*, which is part of *Grasshopper*, a parametric model of an architectural space (*DaylightBox*) and an engine that simulates natural light (*Diva-for-Rhino*). These software tools make it possible to generate architectural solutions that comply quantitatively with interpretations of the designer's intentions. A visualization interface (*DaylightViewer*) makes it possible to sort the solutions and gather their properties. The designer can then assess the proposals by producing photorealistic simulations and verify whether the effects produced correspond to his original intentions.

4.4. Meta-modeling

Meta-models, also called emulators, surrogate models or response surfaces, are increasingly used to simulate and calculate efficiencies, and to simplify complex and costly models, especially in the sketching phase. The first point of interest for modeling the calculation of an efficiency through a meta-model is that all the responses of the study field can then be calculated with no need to make costly new simulations for each assessment (although the differences compared to the real values still need to be verified). The second is that an assessment can be conducted in a negligible amount of time compared to the original simulation. For example, a precise calculation of the lighting within a room takes several minutes, and can be carried out with a reduced model in a millisecond (section 5.8 in Chapter 5).

The starting principle is to use a simulation program with the most precise and reliable estimations possible, validated by the scientific community. For example, analysis of the thermal behavior of a structure (summer/winter, day/night, morning/midday/evening variations, setpoint temperatures and variable uses over time) will be carried out through dynamic thermal simulation.

We will then construct an *experimental design* (section 4.4.2) to create a deterministic surrogate model applied with measurable precision in a limited variation field of samples and parameters. There are also probabilistic meta-models, which can propose predictions outside the experimental design and quantify the uncertainties associated with them [GOU 06]. It should be noted that, in general, the meta-model should be rebuilt if the experimental conditions are altered.

4.4.1. *Choosing a type of meta-model*

Although there is no consensus as to the best choice of meta-model, a few recommendations can be made. Detailed, highly mathematical explanations of each meta-model are outside the scope of this book: the reader is invited to consult the bibliographical references cited.

Linear regression and kriging (called a Gaussian meta-model) [FAI 13] are two different but similar methods for using the available information to create a better prediction. Due to their relative simplicity, polynomial linear regressions are the best-known statistical methods, most frequently used by engineers, especially when the efficiency function to be modeled seems fairly regular. Their sensitivity analysis is also easier. A polynomial with a degree of ≥ 2 makes nonlinear couplings between variables possible. However, the higher this degree, the more experiments must be performed to determine all the coefficients [DEC 09].

Spline-based regressions are useful if we want the function to pass through all the samples. The same is true of kriging, which is a prediction from neighboring data. Unadvisable if the model is particularly nonlinear, its experimental designs are constructed from a fairly small number of simulations [FAI 13].

More complicated to implement, but often highly effective, orthogonal polynomial chaos models facilitate global sensitivity analyses [SUD 14, ARM 15].

Finally, meta-models based on artificial neural networks [GOS 13] are "riding high", and are now used preferentially when the function is relatively complex (*black box* effect). They depend on a large number of functions and may be highly nonlinear.

4.4.2. *Experimental designs*

The construction of a meta-model begins with an initial learning phase defining an *experimental design*. It involves a more or less organized set of simulations, each enabling new knowledge to be acquired by altering the set of input variables. The aim is to obtain/validate an economic model (as few tests as possible) by testing the respective influence of the various variables and their combinations. Many theoretical elements make it possible, using specific models of varying degrees of complexity, to determine at what points simulations must be carried out [MON 14].

In practice, it is easier for a non-expert to entrust this task to a specialized software program, such as *Design-Expert* from Stat-Ease[13]. This produces complete, fractional, orthogonal factorial and Box–Behnken designs. The main feature of the latter is the uniform distribution of experimental points in the study field [BOX 60].

4.4.3. *Sensitivity analysis*

Let us first highlight the omnipresence of imprecision and uncertainties in any model, and therefore in any digital simulation: models are only tools that represent the studied phenomena with varying degrees of accuracy. Besides, *stochastic* uncertainty is inherent in the natural variability of numerous phenomena.

Furthermore, imprecision affects the sampling, filtering and sub-specification of input data. It is still related to the digital resolution of models: division of spaces, type of network, boundary conditions and

13 www.statease.com.

convergence time. Finally, it concerns the subjective assessment of efficiencies, as in [LOZ 11, VIL 12], which take into account in the multi-criteria optimization phase the feelings of users about light perception.

The aim of a sensitivity analysis is to determine the influence of parameters (isolated or grouped) on the variability of the response of a model. Their number has a major influence on the dimensioning of the experimental design, and therefore on the associated calculation period.

Two quantitative sensitivity analysis methods can be distinguished: local analysis through propagation of uncertainties (which consists of assessing the impact on the output of small variations of the input variables), and global analysis, which studies how the variability of the inputs affects those of the output. "*Determining the inputs responsible for this variability using sensitivity indices enables the necessary measurements to be taken to decrease the variance of the output if this is synonymous with imprecision, or even enables the model to be reduced by fixing the inputs whose variability does not influence the output variables*" [JAC 11].

Not many sensitivity analyses are carried out by constructing meta-models in the upstream phase of the project in the field of building [ARM 15, NAU 16], and almost none in architecture. We can cite a study on the influence of climate change parameters on a building at the University of Plymouth [TIA 11]. We have had the opportunity to be involved in this since 2012, as the following explanations will show.

4.4.4. *Study of three recent meta-models*

The following works use statistical efficiency approximations through regressive polynomial models, obtained and validated from the experimental designs constructed using Design-Expert and databases from numerous dynamic simulations. The three models are currently part of the EcoGen2 software program (Chapter 5).

4.4.4.1. *Example 1: thermal modeling of multi-layer walls*

The emergence of new technologies and the appearance of new materials, such as those at a phase change and thin reflective products, have led to the elaboration of refined thermal transfer models on the scale of the various subsystems making up the walls [HUA 06, MIR 13]. A detailed report of these models is presented in [PAS 08].

In his thesis, Mavromatidis [MAV 11] developed a tool to simulate thermal transfer in the envelope, taking into account the conductive exchanges within different materials, the convective exchanges on outer surface and the radiative exchanges modeled using the double-flow approximation method. The original aspect of his work is that heat transfer through radiation across the insulation system (in any air gaps) has been modeled taking into account boundary conditions, and we have a reliable digital model for materials that are both optically thick and thin. During his post-doctoral research at MAP-Aria, he designed a specialized model of thermal transfer through exterior walls to characterize the thermal resistance, R, of a composite wall [MAV 13a, MAV 13b]. This model is available in three versions, according to the number of layers taken into account.

These small models have potential to become simple and effective prediction tools for comparing the thermal resistance of a variety of composite wall configurations. They provide architects and engineers with polynomial equations that allow for a rapid evolution of the energy efficiencies of the envelope in the project design phase [MAR 13b].

However, regression polynomials can be used only in a steady state. To transpose the method into a dynamic state, it could be based on xRyC models. The approach could also be applied to inertia, depending on the climatological nature of the site. A simplified model showing the dephasing of an outer wall of a solution, depending on its main thermophysical components, its tilt angle and thickness, could also be integrated into the assessment.

4.4.4.2. *Example 2: prediction of heating consumption*

Due to the complexity of the problem, predicting the precise energy consumption of a built structure is always difficult. Between 2008 and 2013, Catalina developed various regression models with a view of estimating the heating consumption of a building or private home with a few indicators. As for RT2012, these models do not estimate primary energy, but only the final energy H consumed by the building, in kW/m^3, which has more physical meaning. The inputs of these models are, for example: the form factor of the construction, the G coefficient (volume loss of the building), the ratio of the surface to the ground, the south equivalent surface (*SES*), the ground–air temperature difference ($\Delta\theta$) and the setpoint heating temperature [CAT 11, CAT 13]. The 2013 model, described here, is based on 8748 dynamic thermal simulations for various European climates. It uses the three macro-parameters G, SES and $\Delta\theta$ to produce a quadratic polynomial [4.1].

$$H = 18.454 - 21.498(G) - 1.844(\Delta\theta) + 0.024(SES) + 4.668(G \cdot \Delta\theta) + 0.067(G \cdot SES) + 0.006(SES \cdot \Delta\theta) + 12.352(G)^2 - 0.012(\Delta\theta)^2 - 0.0002(SES)^2 \quad [4.1]$$

4.4.4.3. *Example 3: simplified simulation of natural lighting with the daylight factor/meta-modeling for natural lighting*

> "*The interior quality of a space depends on the amount of exterior space that enters through the intervention of light and transparency*" (Frank Lloyd Wright).

In this field, we generally focus on three types of calculation: the building's ability to allow natural light into its interior spaces, its natural lighting autonomy and the characterization of its summer comfort (often by estimating the number of hours of discomfort). The *International Commission on Illumination* (CIE) recommends the use of the *Daylight Factor* (DF) as the simplest parameter for qualifying the natural light gains in an interior space with windows. It is equal to the ratio of the light received on an interior horizontal plane through daytime gains and the exterior lighting coming in unimpeded from the sky, in the absence of direct sunlight. It does not take into account the orientation of the facade, but only the position of shields in the sky visibility area (any natural or artificial object, near or far, likely to hide the sky at any time of the day: mountains, trees, buildings).

In the upstream phase, this criterion is useful to the architect for estimating the natural light gains of their project (although they do not know all the properties), minimizing the artificial lighting requirements and obtaining correct sizing of the openings for each facade. In the project dimensioning phase, the designer can also use: the surface percentage with a DF > 2% (DF2) and the summer solar gains on glass (SSG, in kWh/m^2). Two other indicators can be used during this phase: DF2/DF, which expresses the abundance and uniformity of natural lighting, and DF2/SSG, which expresses the abundance of light depending on the solar contributions.

A normative aspect relating to working comfort is associated with the DF: this is its optimal use field. With a reference value of 5,000 lux for outdoor lighting, useful indoor natural lighting is fixed at 200 lux, and given a loss of 20% due to attenuation (glass, framework, dust), we count on a gross flow of 250 lux, i.e. a DF of approximately 5%.

The challenge was to construct a simplified model for rapidly calculating DF on a building in a partially shaded urban area, designed using voxels. We will now give a brief summary of this work, published in [MAV 14b].

For each housing unit (voxel), the light reception plane is 0.7 m from the ground and contains 100 targets. The quadratic polynomial regression models [4.2] that we have developed seek to analytically express the DF, based on interdependent variables x_i:

– dimensions of the voxel (by default: 10 m × 12 m × 4 m), scalable;

– number of centered openings on the facade (sufficient approximation);

– type of environment (atmospheric pollution);

– dimensions and depth of shields (centered on the openings).

$$\text{FLJ}(x) = b_0 + \sum_{i=1}^{N} b_i x_i + \sum_{i=1}^{N} b_{i,i} x_i^2 + \sum_{i,j=i+1}^{N} b_{ij} x_i x_j \qquad [4.2]$$

The sensitivity analysis has made it possible to detect variable couplings and eliminate those with a negligible influence. The numerous polynomial coefficients [4.2] are explained in [MAV 14b]. We obtained two regression models that are more precise and quicker to assess:

– the first has five variables, a quadratic polynomial with 21 coefficients, obtained from 41 Doehlert simulations [DOE 70] with the Dialux program[14], which assesses the DF for a voxel with a single opening and a single shield;

– the second has 17 variables, a quadratic polynome with 45 coefficients, obtained from 283 Box–Behnken simulations with Dialux, assessing the DF with a maximum of four openings (one per facade, each with its own shield; Figure 4.2).

14 www.dial.de/en/dialux.

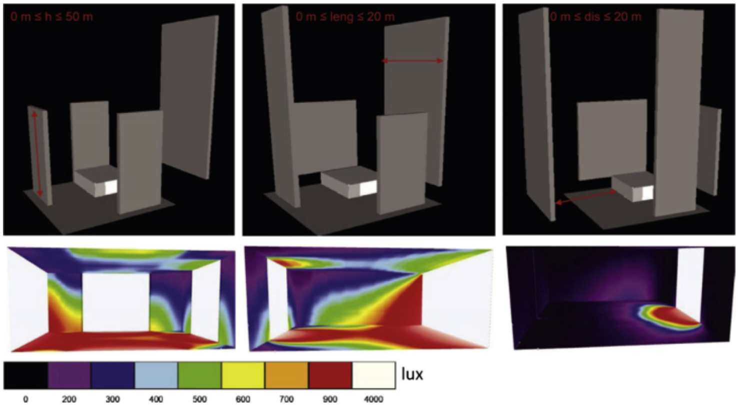

Figure 4.2. *Dialux simulations of interior light of a parallelepipedic volume including a maximum of four openings. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

To finish and validate the precision and stability of the adjustment model (Figure 4.3), an analysis of the correlation between measurements (DF from numerous simulations with Dialux) and estimations using the model has been performed using statistical measurements of the error committed (BIAS = medium difference, RMSE = typical difference) and a series of tests (Cook's distance, Henry plot, Box–Cox plot [MAV 14b]).

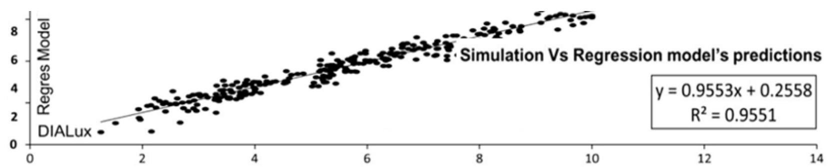

Figure 4.3. *Precision of the adjustment model of the DF calculation*

4.5. Some prospects with major scientific obstacles

4.5.1. *Aeraulic modeling for the upstream phase*

> "*Knowledge of the effects of the urban microclimate on the thermal comfort of buildings is required to create passive bioclimatic architectures, making it possible to decrease the energy intensity and carbon footprint of the buildings. The possibilities for using natural ventilation depend, for example,*

not only on the morphological properties of the buildings, but also on the climatic conditions near the buildings, such as the movement of air and atmospheric and sound pollution. These conditions depend on urban morphology, which has advantages, such as the moderation of extreme temperatures and protection from cold winter winds and the reduction of the summer heat by means of shady roads. In other cases, the 'urban texture' can present disadvantages, such as the stagnation of pollutants, which the urban morphology no longer enables to be dispersed by the dominant winds" [ADE 11].

Today, natural ventilation can be a significant aspect of architectural projects, in order to reduce the energy cost of buildings, preserving the quality of the indoor environment, while improving the acoustic comfort of the spaces. One difficulty in the project phase, when it comes to choosing a natural ventilation system, is being able to quantify, and not only qualify, ventilation inside the spaces in relation to wind direction and speed, temperature distribution outside the building, and the position of obstacles around the building.

One of our aims is to assess as quickly as possible, in the sketching phase, the possibilities for natural ventilation, depending on a certain number of parameters such as the wind direction and speed, the height, orientation and layout of the building, the number and dimensions of the openings, the presence of obstacles and their layout around the building.

Methodology: the urban environment is defined by the complexity of the terrain (topography, relief), and the number of obstacles (buildings, other constructions, vegetation) can be precisely known. The building is defined by its orientation, height and occupied surface, and the dimension and position of its openings. From a basic configuration, the additional parameters that must be taken into account are wind direction and speed and the difference between the indoor and outdoor temperature.

The integration of natural ventilation systems into the architectural design process is located at the interface between a job approach and the physical modeling of natural ventilation. Several studies have contributed to assessing the efficiencies of natural ventilation in buildings, particularly through experimental approaches. Reports of the latest developments in efficiency prediction methods for buildings are provided in [MAN 03], and through digital studies using analytical formulae, empirical and/or semi-empirical models, zonal and multi-zone models, and, notably, complex models from fluid dynamics [TAB 09, HEI 10].

Mansouri provides a tool for sizing a natural ventilation system that can be used from the sketching phases [MAN 03], through simultaneous use of COMIS (multi-zone modeling of air movements) and TRNSYS (multi-zone modeling of the thermal behavior of a building) software programs. Her PhD proposes assessment criteria for air renewal techniques in relation to thermal comfort, air quality and energy saving, and provides a methodology for integrating natural ventilation systems into the design.

But few researchers have worked on the use of simplified HVAC models in the upstream phase. We have found no reference to the rapid assessment of aeraulic phenomena, which it would be useful to combine with a thermal model that is centered less on the structure and more on the interactions on the scale of the building.

Numerous studies into the assessment and optimization of the potential for natural ventilation in buildings adopt a CFD (Computational Fluid Dynamics) model, which has a certain number of advantages:

– it provides the entire data flow;

– it makes it possible to avoid reduced-scale tests (and the problems of scale reduction) because full-scale simulations can be carried out;

– it enables the boundary conditions to be fully controlled and parametric studies effectively integrated;

– it makes it possible to solve 3D problems (close to reality), regardless of their degree of complexity, which prevents the problems of precision caused by the geometric simplification of models.

The use of CFD over the last 30 years has developed alongside the increased calculation power of computers. The first models represented the geometry of the study zone in a very simplified way. Models representing more detailed geometries (e.g. an entire building), then appeared and, finally, models of several buildings representing a neighborhood or even a town.

But one of the major difficulties inherent in CFD simulations of ventilation on the scale of a building/block/neighborhood lies in precisely representing the interaction between the wind flow around the building and the circulation of air inside. We can therefore divide models into coupled and uncoupled approaches. The coupled approach involves a single geometry and a single calculation field, which includes both the outside and the inside of the building. In the uncoupled approach, the simulation of ventilation outside the building is carried out considering the building as a watertight body. The results of this simulation give the pressure coefficients for the openings, and these coefficients are then used as boundary conditions for the CFD simulation and the indoor air flow. For large openings, the uncoupled approach can lead to significant errors, which is why the coupled approach is often preferred.

One idea would be to design smaller models or meta-models, economic in processing times, from CFD-3D models of building simulation, using standard optimization strategies by means of experimental designs. It would consist, through various experimental design methods, of developing meta-models capable of connecting the natural ventilation flow depending on the most influential parameters, such as wind speed and direction and the density and average height of obstacles [SHE 12]. After a validation phase, models developed in this way could then be combined with a thermal model of the building.

4.5.2. *Taking climate change into account in upstream design*

The following account, with high potential for the future, is a recent update of an internal production from the MAP-Aria laboratory, drawn up in 2012–2013, mainly by Lazaros Mavromatidis during his post-doctoral research. These texts, which have not yet been published, deal with different scales of the urban environment. For more detailed information, the reader is invited to consult [MAV 14a].

4.5.2.1. *Interactions between climate change and the urban environment*

The term *climate change* denotes an evolution in the statistical distribution of atmospheric parameters (temperature, humidity, wind) for a prolonged period (decades or centuries), as described in [VAR 14]. Planetary and regional climate and environmental changes have a negative impact on the local scale (territory, metropolis, conurbation). They can take the form of a sustainable evolution of climate conditions, and also a multiplication of extreme or unusual episodes (heatwaves or cold snaps, heavy precipitation leading to floods, hurricanes, etc.). The question arises as to the adaptation of *human establishments* to changing environmental conditions, an adaptation that will take multiple forms to deal with risk attenuation, a shortage of resources, especially energy, production of crops or manufactured goods, pollution and health, or simply the quality of life in urban areas.

On the contrary, human and, especially, urban installations have a significant impact on the global climate and on the near and distant environment, in terms of greenhouse gas emissions, diverse pollutants, global warming, changes in wind and rain patterns, hydrographic disturbances, biodiversity, etc. The urban object itself, through its morphology, constitution and uses, alters the characteristics of its own environment. The form of the urban space and structures that make it up, their materiality and use, and even the activities practiced there cause climatic and environmental changes on various scales. On the level of the neighborhood, this may include the phenomena of heat islands, localized wind accelerations, excessive concentration of pollutants or imbalance of ecosystems. On the metropolitan scale, we will note changes in the characteristics of solar radiation, light, concentrations of pollutants, amplification of extreme phenomena (heatwaves, floods, tempests, storms) and their consequences. On the regional scale, dense urban environments alter atmospheric circulation and composition, affecting the air quality of far more than just urban areas.

Today’s towns were developed based on structural and morphological principles, in which environmental protection and the reduction of the impact of human actions were absent. They are adapted neither to future changes nor to extreme episodes. Unsuited from a point of view of the protection of their components, they will also become unsuited from a point of view of their operational quality. Only hamlets and villages in hostile climates have been able, over time, to develop organizations, morphologies, mechanisms and materials that at least shelter them from the rigors of the climate and extreme episodes [BER 04]. On the contrary, the cohabitation of dense populations in large towns has required specific mechanisms to enable them to work well (orthogonal hierarchized networks, densification, separation of functions, etc.). This has meant that proper adaptation to climate constraints and risk prevention and attenuation has been sidelined.

Thereafter, rapid urbanization has resulted in people commuting to urban areas, emitting increasing quantities of anthropogenic heat, which, combined with inappropriate urban morphologies and the use of traditional materials, such as asphalt and dark pavements, contribute greatly to the increase in ambient temperature throughout the summer period. High surface and air temperatures decrease comfort levels, increase the demand for energy for cooling and contribute to higher pollution loads.

Finally, due to increased attention being paid to the energy consumption of correction mechanisms (heating, air conditioning, artificial lighting), we have recently been rediscovering the benefit of knowledge of macro and microclimatic phenomena and their impacts on living conditions in urban areas, and, therefore, the need to qualitatively and quantitatively assess the impact of urban planning decisions on the local and global climate and, consequently, on living conditions [MAS 00]. In the same way, the alteration of metropolitan strategies aiming to develop practices in terms of mobility (modal shift, reduction of journey time and distance, optimization of routes, etc.) and urban renewal (densification and intensification) contributes to this movement to optimize the natural and energy resources available and reduce anthropogenic impacts on the natural and climatic environments.

4.5.2.2. *Modeling of interactions between climate and the urban environment*

Fairly recent research, including [HUA 12, MOR 15], has shown that:

– the climatic/microclimatic characterization of the urban environment is highly complex, due to the interdependence of five flows: sunlight, dominant winds, natural convection, pollutants and anthropogenic production;

– orography has an effect on the local climate. The position of built spaces in relation to reliefs and expanses of water and their orientation in relation to the dominant winds decrease or increase the effects of global climate change, alter the flow and thermo-hygrometric properties of air, the concentrations of pollutants, cloud cover and intensity of solar radiation [TOM 08];

– the intensity of greenhouse gas emissions and pollutants depends on the location of activities and their energy consumption. The concentration of pollutants, or their non-dispersal due to the spatial distribution of activities, can cause public health problems [KAL 93, AND 06];

– the modification of the geometry and make-up of exchange surfaces (ground and buildings) with the ambient air forms local microclimates (heat islands, windy areas) or more global ones (*canopy and urban boundary layer*), altering the thermals and dispersal of pollutants, potentially causing problems with comfort and health [ELI 06, BER 04, FRA 04];

– urban spaces are neither designed for nor adapted to increased exposure to extreme episodes (floods, high waters, tempests, heatwaves and cold snaps). The heatwaves in Europe in summer 2003 clearly demonstrated the vulnerability of the population and deficiencies in the adaptation strategies, as well as the inefficiency of the built space for protecting against climatic extremes [BEN 03, SCH 04]. Yet, climate change simulations suggest that the frequency, duration and intensity of heatwaves will increase [MEE 04, PAT 05, AND 06, END 06];

– actions altering the urban area (start-up of activities, densification, development of public spaces, planting, modification of surface states) have an effect on sensitive atmospheres and thermal, light and acoustic comfort [HUI 01, DRI 92, GAG 86].

4.5.2.3. *Ambitious objectives for building*

We should consider how a complex phenomenon such as climate change can be integrated into the overall design of the building from the upstream phase onwards. It is no longer enough to design a bioclimatic structure that consumes less energy in the current context: we must also contribute to an adapted design of future climatic evolution, not only in terms of temperature but also of local climate variability, if possible, without having to oversize insulation from now on.

Yet, the design of a building today, in a precise place, is almost never adapted to possible extreme climate scenarios, because the thermal regulations suffer from a lack of anticipation, due to the absence of predictive models in the long term. The models developed by researchers [MAS 09/14, HUA 12] focus on significant interaction phenomena between building, neighborhood, town, climate and environment. However, none of these models are likely to be calculated in interactive time by an appropriate mechanism.

4.5.2.4. *Difficulties*

A systemic understanding of the interrelations between the forms and uses of the town and climate and environmental changes is difficult, due to the numerous uncertainties relating to understanding the complexity of the climatic and environmental system [VAR 14]. Indeed, there has been immense uncertainty as to what the real impact of climate change in the urban environment will be between 2050 and 2100. In this still distant period, a scarcely predictable evolution of anthropogenic, social and economic systems, along with increases in temperature that may reach six degrees according to some models, will come together [MAS 09/14]. If we want our living environments to be adapted to the climate of the second half of the century, we must urgently begin to alter the design of buildings and urban planning strategies.

In the absence of any information on future weather and climate conditions, it is difficult to come up with appropriate architectural and urban responses. When this data exists, a multidisciplinary collaboration is required for the synthesis and analysis of the data to generate useful information. Planners, urbanists and architects lack the knowledge, information and tools required to integrate this attention to environmental changes into their design approach, whether they are designing from scratch or adapting the urban environment to future conditions [GÜN 16].

The current trend is to create approximate models of the energy impact of a structure, making it possible to simulate, in a reasonable period of time, the phenomena on various scales, using predictive climate data (based on medium- or long-term scenarios). For example, the DRIAS site[15] provides local climate projections (predicted for 2050, 2085, 2100, etc.) produced in French modeling laboratories (IPSL, CERFACS, CNRM-GAME).

However, modeling requires information that is not necessarily available, or not on the scale considered: it involves detailed microclimatic observations and the use of adequate models for adapting conventional weather data to the spatial and temporal scales in question.

Thus, Birmingham's "low carbon architecture" model [BIN 14] has been calibrated, using probabilistic weather data, for studying the efficiency of buildings in various future climates. The analysis indicates that climate

15 www.drias-climat.fr.

change will require a robust approach dealing not only with higher summer temperatures, but also lower winter temperatures [HUW 14].

4.5.2.5. *Models and tools for urban climatic simulation in the upstream phase*

Some aspects of climatic simulation tools could be integrated into the software programs used in the design of urban space [CHA 05]. Tools integrating management resources, the use of space onsite and the planning of building construction could provide an overall model managing climatic data and stimulating architectural and urban design. Low-level information on the composition of urban spaces, the dimensions of the building and the circulation of air could be used to generate useful simulations of urban microclimates and test alternative solutions during the upstream phase of urban projects.

Models used in urban planning and design exist, but require considerable expertise [BAN 07, BER 04, CHE 03]. In the same vein, meso-scale weather models can be used to assess the insular climatic and environmental effects of urban heat attenuation scenarios, but they are too sophisticated for decision-making on the urban or architectural scale.

The ambition is therefore not to build an exhaustive model of these interactions on a detailed scale, but to characterize the major parameters of the negative effect of environmental modifications on the town and of the town on the environment. We will seek effective models on the scale in question (neighborhood, block, structure), sufficiently robust to handle the parcel data available in the upstream design phase and sufficiently rapid to be applied to large sets of solutions in a generative approach.

5

The EcoGen Software Program

In the words of architects:

> "*One of the most individual aspects of the work carried out around EcoGen is the attention devoted to the question of the interface between the software program and the architect. The program aims to involve the architect in the optimization process: he can foster the survival or disappearance of certain phenotypes with every iteration, and thus influence the trajectory of the natural selection process, depending on the architectural qualities of the solutions that are offered to him. This approach therefore seeks to overcome the limitations of a computational generative process, by combining it with the architect's cognitive processes. The digital optimization tool can be influenced by elements outside the optimization criteria that govern it, and is therefore a possible design assistance tool. Even inside the workings of the software, there are two major tensions relating to the use of the digital tool: the attempt to find a technical solution to a complex problem using the calculation powers provided by digital technology, leading to the creation of an optimized architecture, and the desire to control and appropriate a tool with restrictive functioning to create unique architectural production, within its cultural environment. In the search for a complex problem-solving tool, it is ultimately the question of the software interface, its ergonomics and its appropriation, guarantees of the success of the symbiosis between calculation process and cognitive process, which seems to be at the heart of this quest.*

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

It is therefore interesting to see, through the example of the work carried out around EcoGen, how an initially technical approach to optimizing a complex problem using digital tools ultimately finds its solution in a reflection on the ergonomics and relationship of the architect and the tool, inviting us to reflect on how the position of architecture is developing in an increasingly technology-based society" (Xavier Bucchianeri).

"*For me, EcoGen has the huge advantage of being very simple to use and having a hidden intelligence that makes it a discreet assistant – one that understands what you want to do, doesn't ask too many questions, and simplifies design – the type of assistant that you can put in your smartphone to quickly come up with a few ideas when on-site*" (Hervé Lequay, scientific manager of the MAP-Aria laboratory).

5.1. Genesis of the project

The MAP Laboratory's research into generative eco-design flourished after the EcCoGen project, *Eco-Conception Générative*, funded between 2011 and 2012 by the *Agence Nationale de la Recherche* (ANR, French National Research Agency) in the framework of the "Creativity: contexts, stakeholders, objects, process" project. This experimental development project united the MAP-Crai, MAP-Aria and Codisant-Sitcom-Interpsy (Université Nancy 2) laboratories[1]. At an institutional level, the project was labeled by the Labex IMU (*Intelligence des Mondes urbains*) in Lyon in 2012.

Initially, it involved two years of exploratory "proof of concept" research, focused on the capacity of evolutionary generative tools to promote the creativity of architects when it comes to designing eco-efficient buildings [MAR 12a, MAR 12b]. In the context of ecological transition, our aim was not to build yet another software program specializing in energy calculations for structures, but to:

– make operational design assistance part of the architect's standard process in the upstream design phase when the project is vague and the data imprecise;

1 eccogen.crai.archi.fr/wordpress/equipes.

– reposition architectural design in the context of designing a structure whose envelope, orientation, morphology and materiality respond to contemporary issues and adapt to an existing built context. The idea is to quickly provide the architect with solutions that satisfy multiple constraints and present efficiencies that develop in the right direction as he manipulates the tool;

– stimulate the designer's creativity by proposing innovative structures and morphologies that are better adapted to environmental challenges, emerging requirements in terms of quality of life, and present and future energy issues;

– promote the emergence of architectural solutions that are better suited to their local context than preconceived "standard solutions" that are then vaguely improved.

The EcCoGen project promoted an interdisciplinary approach and knowledge-sharing between architects, engineers, computer experts and knowledge engineers: cross-fertilization of points of view and methods, construction of more effective theoretical analysis tools and benefiting from the contributions of various disciplines. It has given rise to two independent software developments based on very distinct approaches to generative design: one at MAP-Crai (EcoGen-N), focusing on design based on eco-models, the other at MAP-Aria following in the footsteps of a parametric software environment for optimized solution generation (EcoGen-L, the subject of this chapter).

5.1.1. *EcoGen-N (MAP-Crai)*

EcoGen-N optimizes morphological figures based on eco-models, defined using parametric operators. The environmental strategy implemented is based on 17 eco-models, identified and generated in various ways, through the geometric or physical definition of project elements (rounded form, solar hemicycle, multiple angles, etc.) or the use of specific clusters (nearby patio, corbel terraces, balcony screens, etc.).

EcoGen-N combines a set of processes integrated into the *Grasshopper* tool from *Rhinocéros*[2] in the form of three types of cluster (collections of objects and parametric functions). It involves: 1) generic clusters enabling

2 www.rhino3d.com/fr.

the model to be initialized and visualized, a capable volume generated, and patios and screens created; 2) transformation clusters allowing for deformation operations through displacement, rotation or homothety of the building or floors in a linear or quadratic way; 3) eco-clusters enabling parametric eco-patrons to be constructed.

The input parameters of each cluster can be associated with value intervals, which the designer is free to specify. These intervals can represent the descriptive genes of the analogon. The designer is thus free to construct the genome associated with his parametric model. The genetic algorithm *Galapagos* used here is integrated into the *Grasshopper* software environment. At the end of the process, the designer can take note and visualize the most efficient solutions. He can then modify the make-up of the genome or the construction of the parametric model in order to restart the evolutionary process or export the geometry of the analogon.

The assessment cluster ensures the formatting of the descriptive data of the analogon, the validity of geometric data, the communication of data to the energy assessment engine *EnergyPlus* (essentially thermal assessment) and the storage of information in a database.

This solution offers the freedom of intuitive parametric modeling and leaves the designer free to choose his approach, enabling him to explore his own rationales or morphological references and design hypotheses, and to define his constraint areas where optimization takes place.

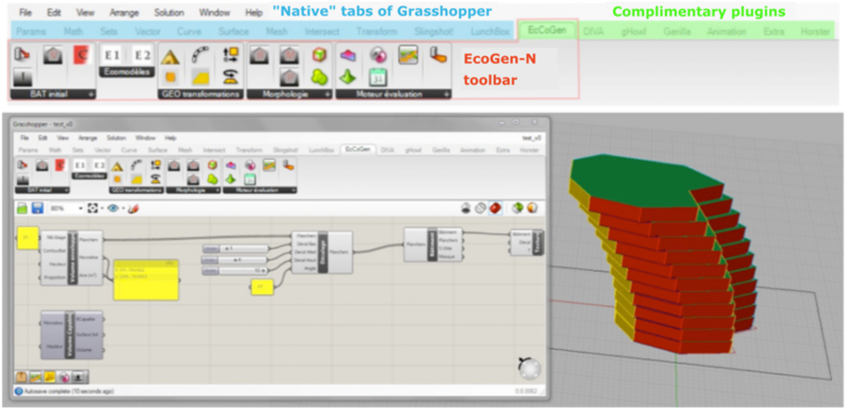

Figure 5.1. *The workings of EcoGen-N under Rhinocéros/Grasshopper. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

This generative approach through eco-models should be further examined. Eco-models, a sensitive and qualitative approach to architectural design, are a structuralist intuition of a proto-architecture that is defined more from the designer's intentions (corbel, patio and atrium, massive forms, continuous surfaces, underground volumes, earth-to-air heat exchangers, etc.), rather like in declarative modeling, but in a relatively unconstrained way, which opens up the field of possibilities, rather than obstructing it. For researchers, a question now arises: how can we build a generative approach for éco.mod based on a list of eco-models to use in morphological generation? The idea is attractive, but has certain conceptual and technical obstacles.

5.1.2. *EcoGen-L (MAP-Aria)*

This is a program that creates efficient forms out of nothing by assembling uniform spatial and functional units distributed in a 3D grid, acting as an available volume for the installation of the architectural program. The forms are selected and assessed by means of various criteria using an interactive genetic engine.

The rest of the chapter will give a detailed explanation of this EcoGen-L software variant, henceforth called "EcoGen".

5.2. General principles of EcoGen

5.2.1. *An original proposal*

EcoGen is a *software wizard* for architectural eco-design, a source of proposals and analytical data, assisting the designer in the creation phase. Its components are designed to reduce the disconnect between the post-design creation and optimization phases by means of a continuous and gradual process.

It helps solve the problem of the lack of tools for assessing the quantitative efficiencies of buildings during the first design phase. In this phase, decisions with the greatest impact are made when it comes, in a given urban and climatic context, to composing the general forms of a structure, depending on various criteria that ensure a sufficient level of efficiency in view of bioclimatic and environmental efficacy requirements, notably relating to energy.

It assists the architect in the project sketching phase, stimulating their creativity by proposing contextualized, evolving solutions for the program, responding to efficiency analyses, and enabling them to choose from a range of possibilities that is often too broad to be examined exhaustively and in a necessarily limited period of time. Unlike building engineering tools, EcoGen is not an *a posteriori* control software program. It is a generative program designed to assist the architect in creating eco-efficient solutions: it "talks" to them to find effective and personalized solutions. The user can direct and guide the search for satisfactory solutions, while keeping in mind the achieved efficiencies.

For reasons relating essentially to small-scale modeling difficulties and calculation times, EcoGen was not designed as a *non-standard* form-generating software program. Chapter 6 will return in part to this question, suggesting some avenues for further research.

5.2.2. *A one-of-a-kind tool*

EcoGen is the fruit of five years of reflection, research, developments and experiments. It is, to our knowledge, the only interactive tool for multi-criteria bioclimatic optimization in the initial design phase, capable of generating one or more buildings in a built environment (block, plot), in an interactive way, with a user-friendly and almost playful interface. Facilitating dialogue with engineering design offices, EcoGen is rapid, powerful, interactive and intuitive. Furthermore, it is autonomous and not based on any paid-for software program.

Thanks to an interactive genetic algorithm and a multi-criteria optimization engine (bioclimatic, ecological, economic), EcoGen offers the architect-user, in the initial design phase, families of morphologies adapted to the local contexts (urban and environmental) and built environment (nearby blocks and plots of land).

However, it is not designed only for formal research or project representation. It is a tool uniting rapid calculation of efficiencies and assistance in design in the upstream phases of solutions to functional, technical and environmental components, combining simplified assessment models, regressive polynomial meta-models, morphological models and interactive genetic algorithms (IGA).

To achieve this, EcoGen has called upon six fields of research with scientific obstacles: eco-design (definition and specification of efficiencies); architectural morphogenesis based on geometric, functional and projective models; reduction of complex models and prediction of behavior; overall optimization of efficiencies through evolutionary algorithms and the search for compromises; human–machine interface (interaction with morphogenesis and optimization engines, multiple visualizations and annotations of solutions, *in situ* perspectives); optimization and parallelization of efficiency calculation algorithms.

However, the solutions proposed cannot be efficient in all the dimensions that make an architectural project successful. For example, EcoGen does not yet assess solutions in terms of construction, functionality, and, still less, sensitive criteria. It does not yet deal with either active technical mechanisms, renewable energies, or eco-construction, essential additions to bioclimatic design by 2020, in order to greatly reduce overall and operational energy consumption. Furthermore, the architect must rework their proposals to address the other constraints inherent in any construction project.

5.3. A generative and modular tool

EcoGen belongs to the family of generative software tools based on population evolution. Its principle is to iteratively generate a number of solutions, using two engines: one morphological, the other genetic. Some solutions, deemed effective, are crossed with each other and/or mutated to generate new ones, which will then be assessed based on certain criteria chosen at the outset by the user and, of course, modified depending on the results obtained.

EcoGen considerably simplifies the design loop: proposal → assessment → modification → new proposal. Like any carefully designed optimization algorithm (section 3.4), that of EcoGen attempts to achieve two objectives permanently: searching through a vast number of diversified solutions and, at the same time, increasing the efficacy of the families of solutions that seem best adapted to the situation.

During each session (also called a *run*), the algorithm builds an initial population that is either random or based on the results of previous experiments. This population evolves fairly quickly at first, rejecting inefficient individuals and generally optimizing the others. It does not provide *the* most effective solution, but makes it possible to find non-exhaustively among a vast range of possibilities, families of solutions that are optimized for the chosen criteria.

Each time EcoGen is launched for the same initial site and program data, the random generator is initialized with a different value. This makes it possible to obtain an approximation of the Pareto front (section 3.4) in just a few *runs* via various convergence trajectories and therefore to temporarily display varied, but increasingly efficient solutions.

5.3.1. *Operating methods*

EcoGen can work in *autonomous mode* (without human intervention, except for pause or stop), and, ultimately, propose a list of optimized solutions for the program and criteria selected by the user.

However, it can also work in *assisted mode* (interactive). In this case, each time the partial results are consulted, the user can tell it which solution/s of those displayed he is interested in, depending on subjective criteria (morphological, esthetic) or objective criteria (efficiency-based, constructive, functional), and thus guide evolution in one or more preferred directions. The software program will then give them more opportunities to *combine* with others for the following generations, using the pheromonal mechanism of choice persistence described in section 3.6. However, although EcoGen tries to preserve the characteristics of the selected objects, it nonetheless continues to optimize the rest of the population, to avoid quickly falling into what we call a “local well” [GOL 89].

The effects of these selections cannot be immediate: several dozen generations are generally required before solutions turn towards a particular morphology. Furthermore, we must not lose sight of the fact that the choice of a selection, if often made based on esthetic (morphological) criteria, can produce less efficient results for certain criteria. This choice is therefore a reasoned act, based, if possible, on attentive study of the solutions presented and noted by EcoGen.

We can, of course, alternate autonomous behavior and interactive behavior by selecting specific solutions and then allowing EcoGen to evolve.

5.3.2. *Modularity*

EcoGen, which currently works only with the Windows operating system, is composed of four modules: an interface, a morphological generator, a genetic optimization algorithm and a fitness assessment engine. Since the 2012 version, EcoGen1 (whose block diagram, shown in Figure 5.2, remains almost identical), real progress has been made in the choice of modules (Figure 5.9) and the rapidity of calculations, mainly thanks to two new and very different programming environments, which communicate intelligently through a *sockets* mechanism, optimized to reduce delays:

– *Java-Processing* [REA 07], an environment designed to write the first three modules, with 3,900 lines of code;

– *EcoGen_Evaluation_Server*, an ultra-fast efficiency assessment program, with no interface, but a console displaying calculation details (Figure 5.3), written in C++/OpenMP, with 4,000 lines of code.

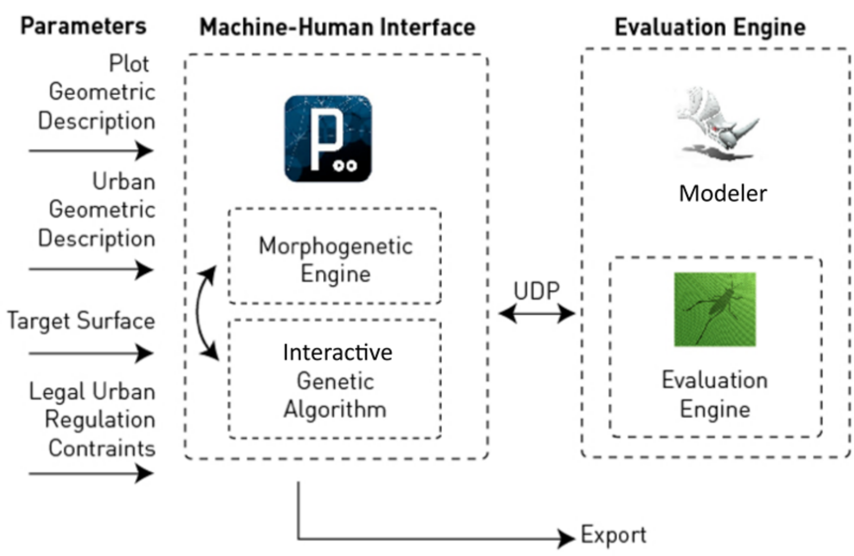

Figure 5.2. *EcoGen1 block diagram*

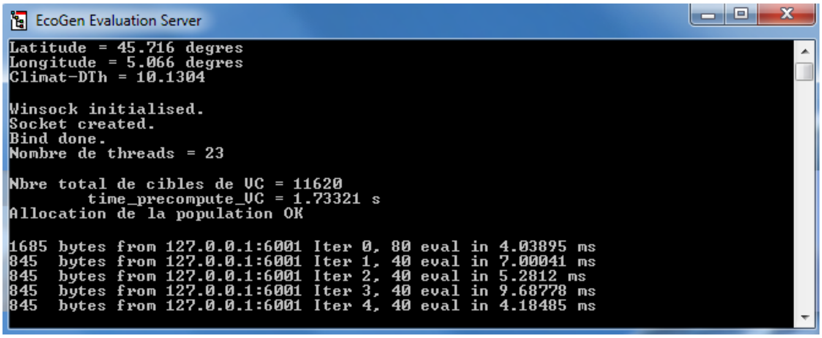

Figure 5.3. *Execution of the EcoGen2 assessment module (extracts)*

5.4. Urban, morphological and programmatic contexts

5.4.1. *Site and operational context*

The operational context is characterized by a place, a climate-solar model (defining the local characteristics taken into account in the solar and thermal calculations), urban constraints and programmatic data. The rules of town planning authorize the construction of buildings following precise constraints: distance from the road, rules relating to semi-detached properties, maximum height and buildable area. These rules enable a capable surface area to be defined (Figure 5.5) and through extrusion, a capable volume, CV (as defined by the architect Rem Koolhaas), adjustable (a specific EcoGen feature).

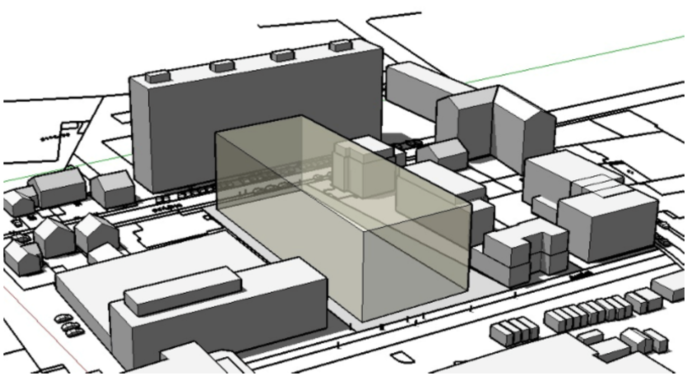

Figure 5.4. *3D view of the (fairly small) urban site in Lyon and a typical capable volume*

When the program starts up, the default operating area is a brownfield site (2012) in the Gerland neighborhood in Lyon (Figure 5.4), and the climate-solar model that of the Lyon region, provided by *EnergyPlus*.

5.4.2. *Morphological and functional description*

EcoGen works in a morphological rationale of modular allocation within the capable volume, now considered a 3D grid to be filled by elementary functional units called *voxels*. Some voxels can be "frozen" (Figure 5.5, pink) to take into account regulatory or alignment-related constraints, for example. According to this plan, a building generated by EcoGen, called a *solution*, is an aggregation of adjustable parallelepipedic units with customizable dimensions. Typically, a voxel may represent a volume of 8 m × 10 m on the ground, and 3 m high (slab to slab). Its surfaces can be material, opaque and sloped, can receive solar and light energy and contribute to heat transfer.

To promote more ambitious and free formal searches, EcoGen2 also allows for quantified rotation of the capable volume (in intervals of 10°) moving any intersections with the built environment (ideally, satisfying a distance constraint fixed by the local land use plan, or PLU). Overhanging forms can therefore emerge from the optimization of solar energy harnessing, interacting with the site (Figure 5.11), thus promoting architectural creativity, particularly in a small or dense environment.

The division of capable space into elementary *voxel* units is also a choice that promotes a simplified implementation of the genetic variation operators and the program's search for algorithmic and calculation efficiencies (particularly for assessment). Indeed, with each iteration, EcoGen generates and assesses hundreds of possible solutions, ultimately proposing only a few to the user. It must do this extremely quickly for ergonomic reasons (section 5.8).

From a semiological point of view, this morphological solution also has the advantage of being an interpretation unit based on a hermeneutic trio:

– *functional unit*: programmatic uses and functions are associated with each voxel. Direct interpretation of the cell in a programmatic unit is possible: this is a software option. It can represent a building for a block of flats (caption: *housing*), an office unit for a service building (caption: *office*), or a retail space for a commercial structure (caption: *activities*).

– *structural unit*: the initial orthogonal grid refers to a structural principle based on a framework of posts/girders. Currently, the structural validity of solutions is not considered, but it could be taken into account by integrating at least one gravity-related constraint.

– *atmospheric unit*: each voxel can be considered in isolation; it is a unitary space whose atmospheric conditions can be stable on the scale of human perception. The implementation of simplified heat or light assessment models is then authorized (uniform unit of volume and wall surface).

The approach is therefore consistent in scale, the voxel becoming the base unit, subject to the interpretations and many readings that the architect can make of the solutions that he observes. He must then take on these solutions and translate the arrangement of the voxels into a formal vocabulary closer to his architectural aspirations (Figures 5.13 and 5.14).

Figure 5.5. *In green: a capable surface of 7 × 4 voxels, 12 × 12 × 3 m, set back from the east and west roads. In pink: non-buildable areas. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

5.4.3. *Description of a program*

An editable "program file" describes the ground area of the plot of land (Figure 5.5, green), the dimensions of the voxels, the maximum number of floors and the “objective surface area” to attain (programmatic constraint). A tolerance can be defined for this via the interface, which is useful for exploring freer forms. The possibility of dividing the plot into *n* separate zones makes it possible to establish a construction program with *n* distinct buildings, the maximum height being, for now, a global parameter. The distribution of the types of voxel use is either free (emerging from optimization) or fixed by the user via percentages. It is then managed by a constraint solver during the evolution process. All these parameters can be altered via the interface.

5.5. Bioclimatic optimization of the generated solutions

5.5.1. *The example of EcoGen1*

The first bioclimatic assessment criteria introduced in EcoGen1 (2012–2013) were relatively simple to implement. The assessment engine was a *Grasshopper* script (Figure 5.6), working under the *Rhinocéros* software program and developed in the MAP-Aria laboratory by Florent Torres, a Master’s student in architecture, to assess three efficiencies:

– compactness, standardized in [0, 1];

– winter energy requirements, through simplified assessment of solar gains and heat losses with the *unified degree days* (UDD) model (see below);

– the shaded area projected by the structure onto its built environment (called *solar courtesy*). This was calculated by a *ray tracer* on a matrix of targets laid out regularly on the vertical facades of the urban context (Figure 5.6), with six characteristic solar positions predetermined for the winter and summer solstices.

The winter thermal assessment was calculated based on the simplified model of UDD [CAR 04], which seemed one of the most relevant in the upstream phase. Indeed, it was a justified approximation in the initial design stage where not all the parameters are identified, with the consideration of solar gains on the glass surfaces depending on the geolocalization of the project and losses through transfer depending on the thermal resistance of the envelope and requiring very few calculations.

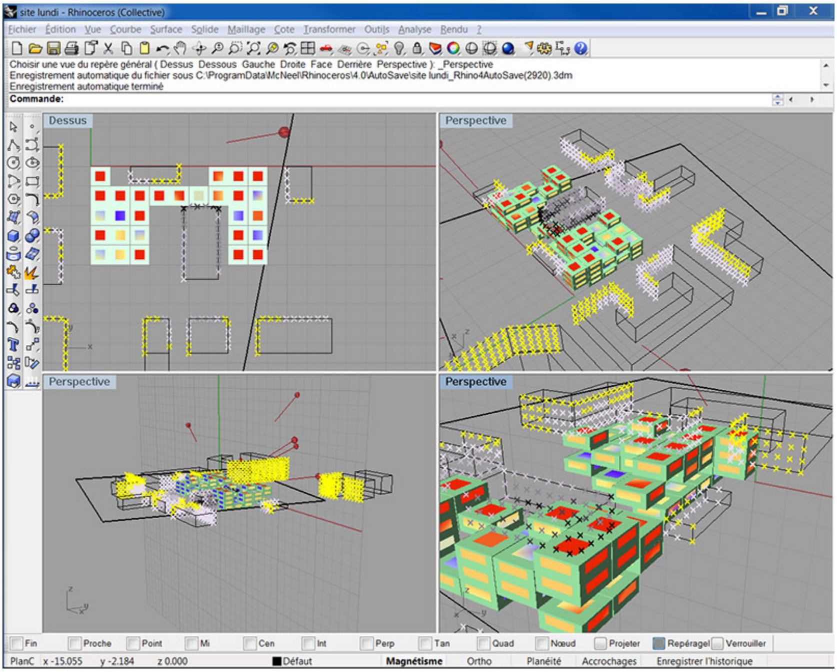

Figure 5.6. *EcoGen I: automatic assessment of the fitnesses of an analogon in the Rhinocéros/Grasshopper calculation environment. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

5.5.2. *Granularity of design*

Very often the materiality of the architectural object is underestimated in the sketching phase although it is a key parameter in energy-efficient design and one of the most difficult to preserve until the planned object is produced. Furthermore, having an idea of certain material details that contribute to efficiency can reinforce the creator's subjectivity during this stage because it is he who explores the material feasibility of his structure based on proposals made by the software tool. This point of view connects creativity (as a dialogue between the designer and the object in which its appearance is often crucial) to eco-efficiency and the future of the "designed" project.

EcoGen1's "white mock-up" has freed us from materiality. Yet, as architectural design is a multi-scale procedure, researchers working on the project debated the idea of using more detailed scales in the sketching phase, thereby exceeding its usual limitations. In doing so, we can avoid extensive modification of the architectural object during the production phase, which often occurs and causes debates between the architects and the design office engineers.

Furthermore, when a bioclimatic design is involved, there is still a tendency to prioritize a fairly constraint-free initial project design (except for normative standards), which will have to be transformed as far as possible into an efficient object before (and sometimes during) its production. Having to correct the object to make up for deficiencies often contradicts the architect's initial creativity. It is not about bypassing the various design offices, whose employees and knowledge contribute to the co-development of the architectural project. However, in this specific sketching phase, where creativity is based on only a few people, it is desirable to have creation support tools that integrate, for the non-expert, a number of useful eco-efficient calculation modules.

For all these reasons, we introduced the option to define the envelope components in EcoGen2, notably to carry out a preliminary multi-criteria diagnosis of its energy efficiency. This decision, which brings us into a summary draft phase, can be a valuable aid for the user's thought process, ensuring that the envelope is efficient for the chosen criteria.

5.6. EcoGen2 assessment criteria

Of course, the strong point of EcoGen2 is that it integrates a much fuller bioclimatic optimization into the initial design phase, based on the overall form of the structure and the specification of certain envelope components. It leaves the realm of the abstract and indeterminate, to which the previous version belonged, proposing more detailed solutions, although the current state of interface development does not yet enable all these components to be visualized.

Let us remember that EcoGen2's bioclimatic optimization begins by taking into account the overall orientation of the building, its layout, the tilt and degree of openness of its facades, and its screening effects, in order to boost solar gains (in the heating season, at least, because the bioclimatic quality of a structure always behaves correctly in winter). Efficiency assessment focuses on natural heat and light gains. Heating requirements are then assessed based on the intrinsic thermal qualities of the building, independent of any active system and the occupancy of interior spaces (this data is very vague in the initial phase of the project). However, as we take into account a division in usage types, we could calculate artificial heating and lighting consumption still more precisely from the sketching phase.

At this level, we are interested in neither the addition of technical atmospheric control mechanisms (some of which can have a significant cost, although they lead to a decrease in consumption and better comfort), nor active cooling mechanisms (whose use is really justified only when summer temperatures become extreme, and in very hot countries).

EcoGen2 generates solutions that are (at the time of publication) compromises in the Pareto sense of four criteria relating to bioclimatism. The models were explained in detail in Chapter 4; we will therefore recall only the essential points here:

– *the compactness of the generated volumes*. We opted for the non-dimensional version of compactness (section 2.5.1).

– *prediction of heating consumption*.

Between 2008 and 2013, the researcher Tiberiu Catalina carried out a series of studies aiming to predict with quantifiable precision the thermal behavior of a building depending on a few macro parameters, and its energy consumption [CAT 08a, CAT 08b, CAT 11, CAT 13]. The sketching phase thermal efficiency calculation module of an EcoGen2 building solution is based on its regressive meta-model from 2013, the most versatile so far, because it is validated for a wide range of configurations in Europe [CAT 13]. Following numerous conversations with the author, we were able to improve and enhance the model by means of developments between 2015 and 2016, to take into account new situations. For example, the thermal assessment engine currently takes into account the built environment, in a similar way to the solar gains engine.

The orientation and slope of the envelope surfaces in relation to the sun for different times of day and year, and the composition of the envelope components (type of material and glazing), are parameters that are integrated into the *G* and *SES* variables of the meta-model (section 4.4.4.2) to estimate thermal gains and losses. For each usage type (office, shop, home), EcoGen2 uses a realistic parameterization whose properties (surface, glazing, insulation) depend on whether or not the building faces south, but, for now, remain fixed. Indeed, in the absence of an economic criterion limiting excess and also to avoid an overload of genetic calculations, these parameters are not subject to genetic evolution.

For more difficult calculations, notably dimensioning, one option is to replace the thermal resistance of a wall in Catalina's 2013 meta-model with one of Mavromatidis's polynomial meta-models (section 4.4.4.1), assessing the thermal resistance of multi-layer walls depending on the thermophysical properties of the materials (density, thermal conductivity, porosity and emissivity), and on the wall's vertical tilt angle and thickness. These parameters, peculiar to each usage type or facade, can be integrated into the evolutionary engine as genetic traits of solutions when the parametric optimization mode is activated.

– *the solar gains received by the envelope of all the buildings on the site*.

The question of the "right to sunlight" is partly dealt with ahead of the project because the Contracting Authority often dictates its location, which is chosen to fit in with the right to sunlight constraint, which is part of urban regulations. However, for reasons of efficiency and creativity, we enable this volume to have several possible orientations, even making it capable of intersecting the built neighborhood (this is, of course, excluded for voxels, each of which respects a distance from the existing structure as per the local land use regulations).

EcoGen1 obtains a compromise between maximizing *solar courtesy* on nearby buildings and maximizing the solar gains of the solutions generated. This requires two contradictory fitnesses to be calculated and maintained. In EcoGen2, overall solar gains (direct, diffused and reflected by the ground) are now assessed and optimized on the scale of the local site, and not the structure, via a single fitness. The solution implemented consists of maximizing the overall solar gain of the site received by the built envelope (including roofing, above-ground), for example, in the heating season, without prioritizing any particular building. Separate optimization of *solar courtesy* is therefore no longer necessary.

This principle complies with the emerging questions of the collaboration of buildings in energy production and consumption (eco-neighborhoods [YEP 11], *smart grids*, new positive energy buildings from 2018 in France) and the reduction of heat islands. It is adapted to energy mutualization, necessarily based on the total gains of the site, especially when the construction schedule on a plot is spread over several years.

Overall solar gains are calculated based on a simplified use of the exact irradiation model described in [ASH 09]. The fitness used is equivalent to the efficacy of the envelope's harnessing of solar energy. We can easily deduce the "photovoltaic potential" of the roof and/or facade from this (section 5.9.6).

Another important point: in bioclimatic design, we often seek to minimize solar gains in summer to decrease peak temperatures inside buildings. This aim is generally opposed to that of maximizing gains during the heating season (October–April in Western Europe). However, in the context of global warming, this minimization of summer solar gains could soon no longer mean anything, especially given the excellent level of insulation that we now know to expect from the envelope. However, above all, to move towards low-environmental-impact, energy-positive buildings (aim of the E+C- reference), it can be useful, depending on the type and location of the project, to maintain a good level of solar gain during this period in order to have enough local energy (e.g. photovoltaic) to fuel the cooling systems. We therefore no longer have a contradictory winter solar gain/summer solar gain ratio, which makes it possible, among other things, to decrease the number of efficiencies assessed at the risk of extending the solar gain duration taken into account for the whole year.

– *promoting natural lighting inside the building.*

Introducing a "daylight factor" (DF) efficiency makes it possible to optimize the orientation, exposure and natural lighting potential of an architectural form in the sketching phase. Let us remember that in sizing, the DF is used to guarantee comfortable and uniform natural lighting in an interior space with openings and to minimize its artificial lighting requirements. At this design stage, the model that we have developed (section 4.4.4.3) simplifies a complex calculation and provides a fairly precise and rapid response. It does not claim to deal with all the variables required for a complete calculation of lighting. However, it assists the architect by providing him with an "equivalent glazed surface" per wall, a sort of guide for positioning openings on the facades at his convenience: influencing the number, location and dimensions according to how the areas are used, with this tolerance being justified in the sketching phase. In practice, the DF is assessed for each voxel, then aggregated into an efficiency that promotes natural lighting of buildings as far as possible and helps decrease electricity consumption.

5.7. Interface and interactivity

The sophistication of efficiency assessment engines and generative engines charged with exploring a vast range of possibilities must be met with simplification and maximum intuitiveness of the interface. It must present theoretical results that are often complicated to read (multidimensional), but are made accessible, using suitable indicators, to non-experts, who must be able to use them confidently and be alert to the possible consequences of poor choices. The relationship between the operator and the software environment is therefore as important as the functioning of the program itself.

The multi-visualization of data, the contextualization and the representation of efficiency concepts are at the heart of the problems, as are the links between efficiencies and morphologies. Our work has therefore been carried out in view of presenting the user with multidimensional indicators, initially facilitating the understanding of connections between forms and efficiencies, and more effectively guiding its interaction with the generative process.

Finally, as it is almost impossible to visualize multidimensional Pareto fronts, it may be processed in groups of two fitnesses, since this is how most decision-makers perform analyses [RIV 13]. We have yet to find a subtle way to present these images without overloading the interface.

5.7.1. *Description of the interface*

The EcoGen human–machine interface enables the user to control the entire evolution process and interact with the genetic algorithm and the calculated populations.

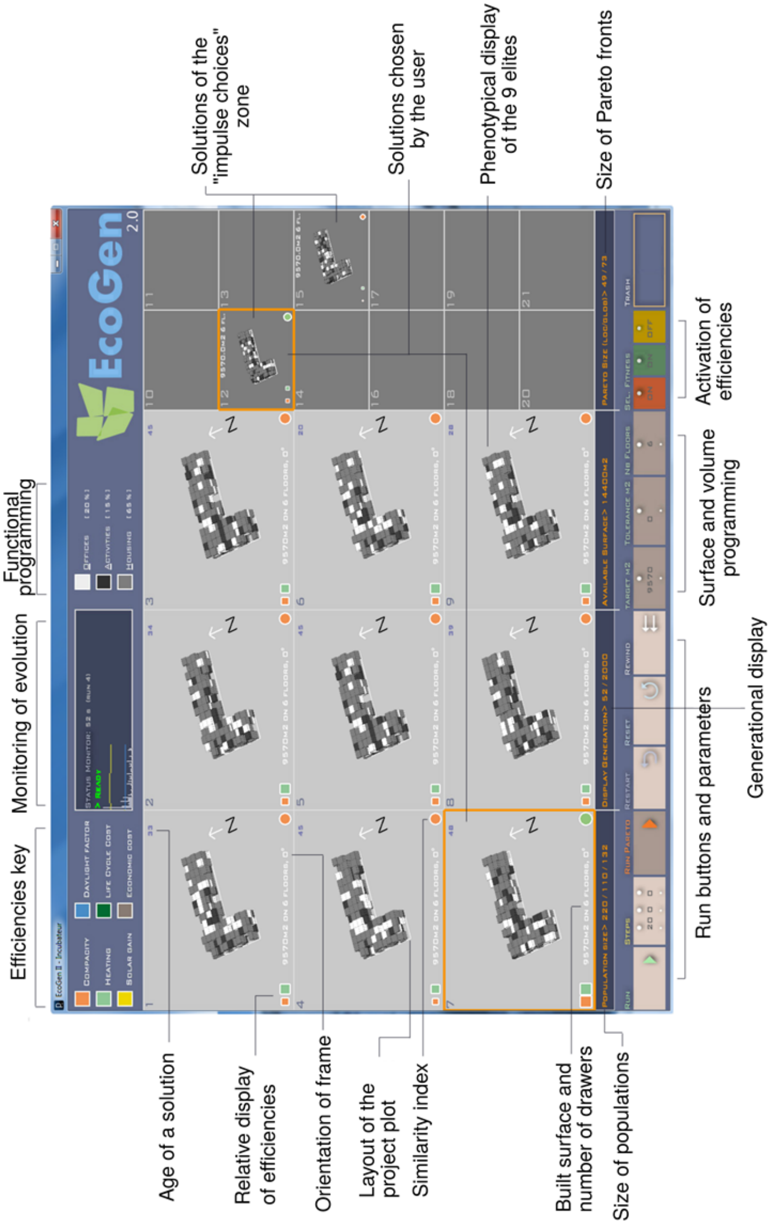

Figure 5.7. *View of the whole EcoGen2 interface, with display of elites and impulse choices (©MAP-Aria, Renato Saleri). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

It is made up of two moveable screens: the incubator, which provides a visualization of an elite population (Figure 5.7) and the perspective view (Figures 5.10 and 5.11), which zooms into the selected solution, making it possible to observe it in its urban context and move around it. In each view, a transformation of perspective – identical orbital rotation for all solutions – enables them to be compared from different points of view. We can also break them down into layers of voxels to visualize the interior.

For each individual, two levels of information are proposed. The first is the phenotypical representation of the solution (3D geometry), which can be manipulated through orbital rotation and assists with subjective interpretation. The other is the relative efficiency profile of the individual, which represents an objective and comparative knowledge base of each individual within the population. The designer can, at any time, select one or more solutions from the population of elites or memorization zone to guide the evolution in directions determined by their phenotypical properties, their efficiencies and the temporal continuity of similar choices. He can also remember the individuals that he wishes to preserve, which may later be selected to redirect the optimization.

On start-up, the main window shows the layout of the project on the ground (Figure 5.5), in the *incubator*. Here, the EcoGen interface is broken down into four main areas (Figure 5.8):

– In the *proposal zone*, the "elite" solutions proposed by EcoGen are displayed, preferably chosen from the "Pareto front" of the population. Only nine solutions are chosen and displayed in a 3×3 square for better visual comfort and to prevent the decision-making process from becoming too cumbersome. They represent, for each iteration, a good sample of the variety of morphological families of the Pareto front, both diversified and efficient. Each is marked by squares of color, indicators corresponding to the efficiency criteria, selected from compactness, heating consumption, solar gains, interior light, etc. This graphical notation method produces an indicator of relative efficiency: the larger the square, the better the efficiency. The user can therefore identify and prioritize the solutions that are more efficient in terms of one or more criteria or those that are equivalent across all the criteria. Finally, the surface area actually affected is displayed for each solution.

Figure 5.8. *Interface: the four main zones of the incubator. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

To help the user in interactive mode, for each elite, EcoGen displays an indicator of the consistency of the choices based on overall resemblance, in the form of a colored disk (section 3.6). If the disk is green, the solution is in line with previous choices. If the disk is red, it is quite different. If it is orange, a compromise has been made. This indicator is very useful for helping the user to make new choices. Notably, if all the resemblance indices displayed are bad for several successive iterations, this tells the user that the choices made are no longer consistent with the previous ones, which can help him correct his approach, if he wants to.

– The *command zone* makes it possible control the behavior of EcoGen.

– The *information zones* specify the graphic codes used, provide information on the status of simulation and programmatic data of the session.

– The *impulse choice (or memorization) zone* makes it possible to store up to 12 solutions for the duration of the run. They are therefore preserved and can be designated in interactive mode as templates in a later generation, or saved.

The EcoGen interface therefore manages three populations:

– the standard population, of variable size, *P*, from a few dozen to a few hundred individuals (P is adjusted dynamically depending on the number of genes). Initially created to be pseudo-consistent with the programmatic constraints, it can also be initialized from the overall Pareto front *M*, in view of thorough optimization;

– the selection *S* of small "impulse choices" (twelve cases): this is the population of "elites prioritized" by the user, but which no longer undergoes evolution;

– the overall Pareto front *M* of all the runs launched with the same parameters, which can be visualized on demand.

5.7.2. *The command zone*

EcoGen allows for more extensive optimization, if the user desires it, starting with the best results from previous sessions. The "RUN PARETO" button launches the work session from the *overall Pareto front*: these solutions are loaded in the initial population and other random solutions are produced if the algorithm deems them useful for supplementing the initial population.

The *monitoring zone* makes it possible to monitor the evolution process. The time of each run is displayed. A message in green indicates the current status of EcoGen.

Finally, a graphic with vertical bars shows the level of population evolution based on the generational comparison between two successive Pareto fronts in the fitness space. This measure involves adding up the

Euclidean distances between the closest elements in the two fronts. It is robust and works even if the fronts are differently sized. A bar extending beyond the blue line indicates a significant evolution, while a bar beneath this line shows a minor evolution. A decrease in the frequency of the bars denotes a convergence zone, which may be local (well). As for the yellow curve, this is a measure of control of the diversity/efficiency of the ACROMUSE module (section 3.5.4). Based on a mix (SPD, HPD), it makes it possible to verify, through its regularity (normal status), the stability of this measure during a run.

5.7.3. *Launching a new session*

A session begins when a file coming from the *Program* directory is drag-and-dropped into the proposal zone of the main EcoGen window. In particular, this kind of file defines the capable surface, a maximum extrusion height and the dimensions of the voxels. This is, therefore, the time to use the interface to adjust the program parameters: surface to build on, surface tolerance, maximum number of floors, usage type constraints (optional) and choice of efficiencies to be optimized.

When the *Run* button is clicked for the first time, the program creates a random initial population whose size suits the program parameters. At the end of this phase, nine solutions are displayed in the proposal window, and the genetic evolution process then occurs automatically and iteratively. During the first phases of the session, the solutions are not very efficient, except by chance. Depending on the size of the project, a few dozen (or a few hundred) generations might be required before efficient solutions start to emerge for one or more criteria.

5.8. Assessment of "high-efficiency" solutions and calculations

Designing a decision-making support tool accessible to architects requires the creation of calculation codes that are fast enough to assess large quantities of data in interactive time and robust enough to work with incomplete or imprecise data [EIB 03]. Furthermore, the speed of the assessment calculations greatly influences the waiting time for the user of the program. Yet, in the vast majority of cases, the assessment is the link in the chain that requires the longest calculation time in running an evolutionary algorithm.

Furthermore, algorithmic efficacy, which is always crucial, depends greatly on the architecture dedicated to parallelism. It is generally trickier to obtain using a GPU (graphic processing unit), whose specific memory architecture regularly imposes major constraints on the developer. For around a decade, the use of highly parallelized GPUs has made it possible to increase by several orders of magnitude the most consuming phase of a genetic algorithm: efficiency assessment [MAI 11]. However, the task is often difficult and unsuited to building assessment algorithms and the code is not very stable in time.

On the other hand, multi-core CPU (central processing unit) parallelism has existed for several years and makes it possible, without being fitted with a high-end graphics card, to obtain gains that are linearly proportional to the number of cores. And with Intel Xeon Phi cards[3], which can each contain several dozen cores, the efficiencies can be fairly substantial.

The slowness that affected the interactivity and overall ergonomics of EcoGen1 (an obstacle to the creative aspect of the system) was rectified between 2013 and 2015. The processing speed has been increased by a factor of 1000 since the first EcoGen1 prototype, by combining algorithmic efficacy, simplified modeling, meta-modeling and parallelization of calculations on CPU. The magnitude of an assessment of the three bioclimatic efficiencies is currently 1 ms per solution on a recent computer fitted with a four-core CPU.

This gain of three orders of magnitude (including two on the algorithmic level) has been made possible through the combined use of C++/OpenMP libraries[4] and increased algorithmic efficacy, obtained jointly by optimum geometry-describing structures and the use of polynomial meta-models. We have designed the most generic possible C++ classes to avoid reprogramming everything if the morphological model is changed. This has also made it possible to process larger projects and discretize the capable volume more accurately.

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3 www.intel.fr/content/www/fr/fr/products/processors/xeon-phi/xeon-phi-processors.html.
4 www.openmp.org.

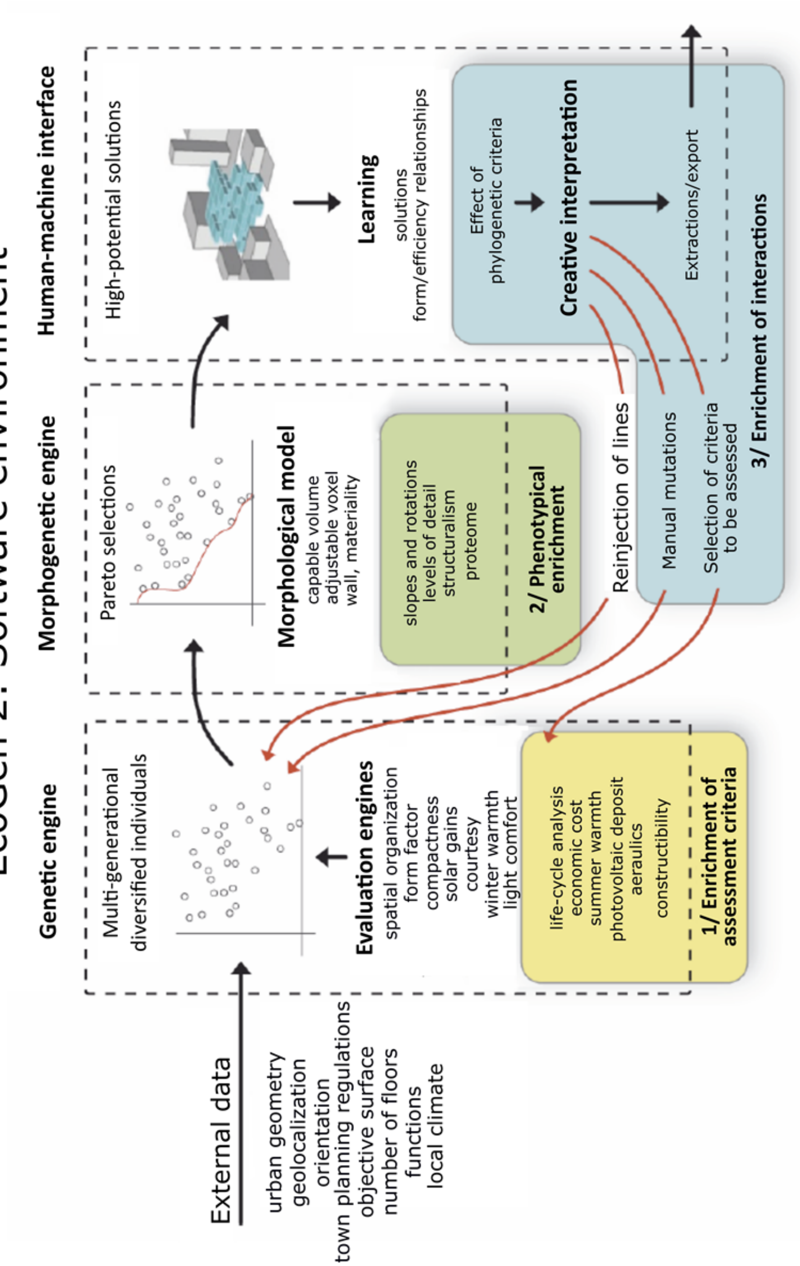

Figure 5.9. *Current status and evolution (colored bubbles) of the EcoGen2 software program. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

5.9. Short-term prospects

5.9.1. *Eco²Gen: a future prospect for project eco-design and economics*

Currently being developed (Figure 5.9), *Eco²Gen* will be the most robust version of our program for eco-design. It aims to optimize efficiencies that are now concentrated around three aspects: energy, comfort and overall cost. Two efficiencies are currently being developed (as they appear on the interface): environmental cost (approach relating to a summary *life-cycle analysis*) and *overall economic cost*, estimated over the life cycle. Minimizing the overall costs (ecological and economic) involves a summary LCA (current scientific obstacle), including an estimation of the carbon footprint. Finally, the improvement of summer thermal comfort and the introduction of building rationales (currently absent from EcoGen2) will soon supplement the range of assessable efficiencies. Materiality does not concern only wall composition; it is also closely connected to the building system and inertia of a structure.

5.9.2. *LCA in the sketching phase*

In the architectural sketching phase, with the exception of VizCab (section 2.6.5), no generative software program seems to incorporate a summary LCA approach.

We have seen (section 2.3.2) that verification tools such as *novaEQUER*, *ELODIE*, *Bilan Produit* and *BEES* are more suited to the advanced design phases (significant expertise required, a large quantity of precise data to be provided). However, Peuportier confirms that these tools can be used upstream, using generic data (material property averages, for example), in the summary draft stage [PEU 13a]. Similarly, Gobin highlights that *EQUER* can make it possible to "*carry out a prior LCA on the basis of an initial sketch, so as to define the challenges and validate the objectives used, from the programming phase*" [GOB 11]. The two authors, however, avoid one central question: that of the reliability of results in the upstream phase with basic and not very precise data (50% precision at best – is this reasonable?).

Initially, an LCA limited to the envelope materials would make it possible to compare the environmental quality of multiple solutions whose efficiencies may be close from a point of view of form, functions and energy consumption during use. Then, the addition of an overall project cost is mandatory for limiting the onerous technical solutions that emerge from optimization (e.g. outsized windows to capture light, triple glazing, efficient materials). We can therefore define limit thresholds for: 1) number of windows (initially to limit costs in the absence of an economic assessment of the project and promote summer comfort), 2) excessive insulation for winter requirements (in the temporary absence of summer comfort assessment, to which over-insulation may be detrimental).

5.9.3. *Assessment of solar energy potential*

One objective that has been fairly easy to achieve since the development of "*target computing*" (section 4.3.4) is the rapid assessment of the solar potential of a site and its energy production capacities, according to the solutions generated. Here too, one of the issues is processing speed. Concerning the assessment of a site's solar gains and buildable plot of land, we have demonstrated the feasibility of very rapid calculation during the development of EcoGen2 with simplified modeling based on adjustable voxels. However, this is already a highly promising breakthrough for other types of morphological model because the assessment engine takes into account the availability, orientation and slope of envelope surfaces and the shade levels due to near and distant screens.

In the context of estimating the solar potential of the site/building, targets may be automatically labeled (roof, facades, use of support voxel or neighboring buildings). Furthermore, the shade level over time is calculated directly from the upstream pre-calculations. Another advantage is that, in the interface – by means of a transmission protocol for this more abundant data to be set up – the results of the calculations can be accessible during a pause for the display of energy values by targets, openings and walls (via bilinear interpolation, for example).

We must then estimate the annual energy production for thermal and photovoltaic systems from the solar gain assessment, and characterize the data required to identify the best areas to place solar panels. The tool must assess the share due to solar energy in the production of the system (buildings and/or islands) and attempt to achieve "energy-positive" efficiency. A high-energy-efficiency island currently has an overall energy efficiency of less than 25 kWh EP/m²/year, for the following five uses: heating, cooling, domestic hot water, lighting and ventilation.

5.9.4. *Interactions*

While the materiality of the envelope is not demonstrated, the EcoGen approach lends itself well to interpretation of the volumes and forms by the architect, who takes the generated solutions and translates them into his own conceptual vocabulary (at the risk of sidelining efficiency indicators based on the fact that the generator optimizes the solutions). However, an approach that supports informed creativity must allow for:

– producing details of each component of the envelope (nature, insulation, thickness, type of material, number of windows, energy received or lost, etc.) on demand;

– interaction among components, which is technically trickier to carry out so that the architect can manipulate his object, select materials, for example from a database (local or remote) and guide the evolution more effectively based on his choices;

– manually modifying a solution from its genotype or phenotype. This has not yet been programmed for reasons of interface simplicity and because it requires the structure of the genetic algorithms used to be revisited in depth.

As far as we know, such capacities in the upstream design phase with an evolutionary tool do not yet exist. They could reinforce the success of Eco^{2}Gen and give the creator the advantage of selecting geometric elements and materials based on his inspiration, guided by a broad display of assessments.

5.9.5. *Prospects for moving beyond the voxel-based approach*

The voxel composition method is often chosen for its aggregate logic, similar to conventional project strategies in architecture. However, the solutions represented by boxes (even adjustable ones) carry a formal image corresponding to an architectural style with connotations and which is even old-fashioned, despite the reminiscences found in highly modern architectural production (the Confluences neighborhood in Lyon, France, for example). Formal and material interpretation, and therefore creativity, can be reduced. Let us remember here that the aim of the ANR EcCoGen project was to explore other phenotypical representation codes to facilitate creativity.

The difficulty also lies in the need to spatially represent the solutions, allowing the architect alone to interpret these "capable volumes" in his own architectonic language. We might imagine, for example, letting the user choose between various morphological representation methods (boxes, spheres, points, facets, vectors, grids, point clouds, etc.), or producing these forms in the various architectural vocabularies [ABE 14].

However, in doing this, we greatly alter the nature of the envelope elements on which the efficiency calculations are based, which potentially creates other problems for which we do not yet have a solution. It is always difficult to create morphological models adapted to the envisaged physical models and satisfy the architect at the same time. Avenues for research are outlined in the next chapter.

5.9.6. *Phylogenetic representations of design dynamics*

Some architects who use EcoGen believe that the dynamics of populations as well as the points of interaction with the user are traces of the history of design, a sort of memory of the hypotheses formulated, rejected or accepted by the user. Like a study book, this memory contains abandoned directions that the designer may want to explore later, either to find inspiration or when the avenue taken proves fruitless.

This "phylogenetics of the sketch", which is important for architects who often explore several connected directions and need to return to earlier points in the process to test and compare other directions for research, is currently unexplored. In terms of ergonomics, only a "*rewind*" button is present in the interface. Of course, we must consider ways to explore, understand and represent this memory in order to facilitate the designer's activity. Sorting and selection mechanisms within populations help us to understand the phylogenetics of solutions.

5.10. Experiments, results, development

5.10.1. *Results*

The following illustrations present concrete examples of autonomous optimization with EcoGen2 (from the Pareto fronts of emerging functional configurations), for two fictional construction programs on the Gerland site in Lyon (respective imposed surface areas of 12,080 m^2 on at most 16 floors – Figure 5.10 – and 22,800 m^2 on at most 20 floors – Figure 5.11).

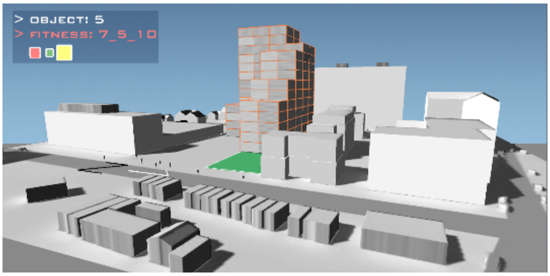

Figure 5.10. *Perspective view in EcoGen2, construction project of 12,080 m^2 over at most 16 floors (for the structure colors, see the caption of Figure 5.8). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

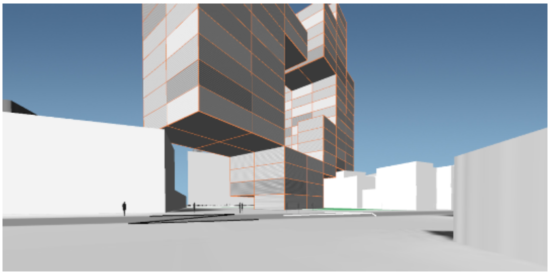

Figure 5.11. *Perspective view in EcoGen2, construction project of 22,800 m^2 over at most 20 floors, with acceptable overhang. The hollow space that emerges at the center promotes solar courtesy (for the structure colors, see the caption of Figure 5.8). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

It cannot be denied that the integration of ACROMUSE into EcoGen and the improvements that we have made to it (multi-objective extension and refinement of parametric adjustments) are two of the strong points of this work, initially aiming to foster creativity, and therefore benefiting from an ability to optimize in diversity. It has been meticulously tested with all the combinations of objectives.

Figure 5.12 shows an example of optimization on three energy objectives (heating consumption, solar gains and compactness). The program is built on 10 floors maximum with an imposed surface area of 8,040 m^2 and 17 well-diversified Pareto individuals are obtained after 1,000 iterations.

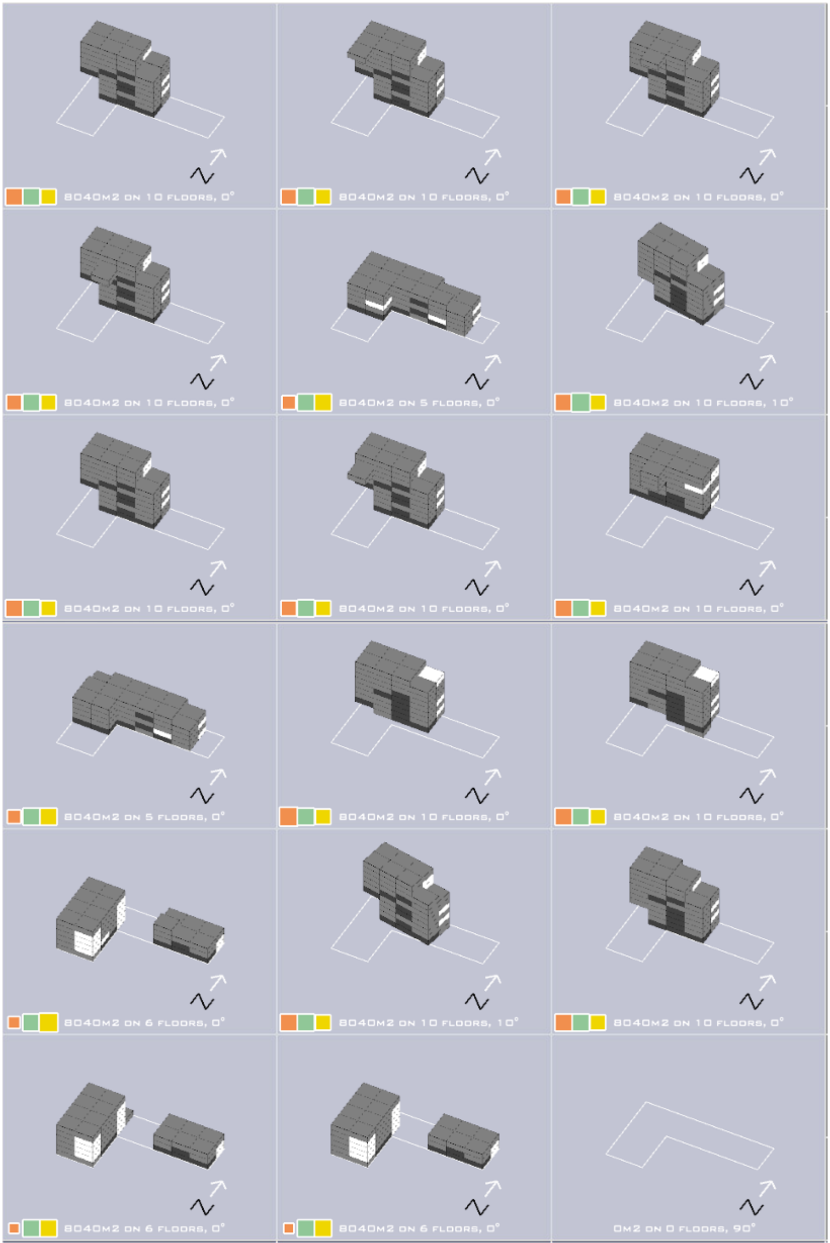

Figure 5.12. *Example of exploration of a Pareto front: construction program of 8,040 m^2 on at least 10 floors, 17 optimized, fairly diversified individuals (for the structure colors, see the caption of Figure 5.8). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

5.10.2. *Assessment of creativity in an evolutionary design environment*

Between 2012 and 2015, the MAP teams carried out a series of experiments with approximately 100 Master's students. The first experiments, which were supervised by the Codisant laboratory, gave rise to video recordings (Figure 5.15), questionnaires and interviews. This cognitive psychology laboratory sought to assess the stance of designers using EcoGen and the methods of solution emergence, and to characterize some of the creativity mechanisms implemented over the course of the sessions. The analysis produced the following results:

– based on eco-efficiency criteria and planning constraints, EcoGen makes it possible to browse very open spaces: the tool produces unconventional and sometimes unexpected or unpredictable morphological solutions;

– it makes the operator-designer aware of questions of ecological efficiency, which he generally considers only later in the process;

– it makes the designer think about the hierarchy of efficiencies (heat, light, morphological). Architecture students are aware of environmental concerns, but lack the knowledge and analysis tools required to be at ease in these fields. They consider EcoGen an aid to better understanding the relationships between form, matter and efficiencies, which contributes to the implementation of educational methods and tools for developing their skills in the design of effective and eco-efficient structures;

– it questions intervention scales: should we prioritize the form and overall efficiency of the structure – which tends to produce version I of the software program – or should we consider smaller scales (the functional unit of the home or office, for example), the expected and obtained efficiencies being strongly correlated to the local characteristics of the cell (orientation, exposure, exposed surface area/protected surface area ratio, altitude, adjacency)?

– it questions the requisite degree of interaction between the designer and the tool, notably in terms of the preliminary knowledge required both in the field of eco-efficiency and in the understanding of solution emergence, selection and optimization mechanisms and the degree of intervention that this knowledge makes possible (trust in the tool, selection of families of solutions inconsistent with those expected from the program, etc.);

– finally, it questions and leads the designer to question the place of creativity in a process in which it is initially the tool that creates the formal solutions.

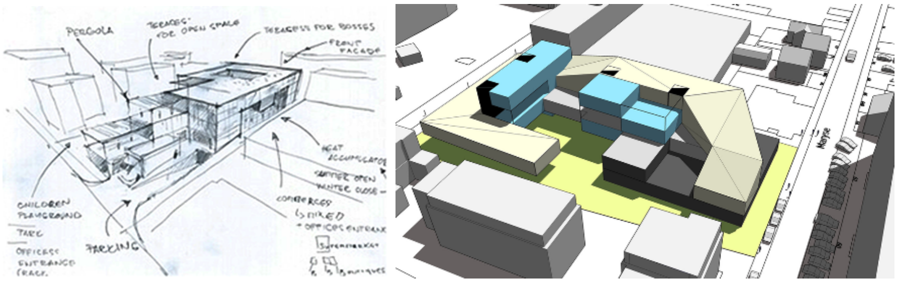

Figure 5.13. *Objects expressing reworked proposals. Experiments of April 2012: a) sketch from an annotated perspective, b) objects expressing a reworked proposal with Sketchup software. For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

The experiments conducted in 2014–2015 in the framework of the PALSE/MapCOD project, supported by the Rhône-Alpes region in France, have increased interest in the EcoGen tool for training students. During a time-limited exploratory process (three lots of three hours), they were able to assess its ability to propose optimized morphologies in a design exercise in the sketching phase from urban and programmatic data. One aim was to assess the impact of EcoGen on the project practices and perceived creativity of the students. All these tests led to the improvement of the tool (2014–2015), particularly with a view to efficiency.

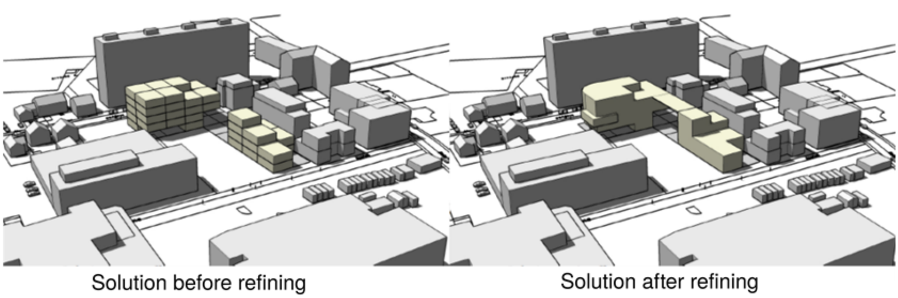

Figure 5.14. *Objects expressing a reinterpretation of a solution proposed by EcoGen. Experiments of May 2014: a) rough sketch, b) arranged sketch*

5.10.3. *Morphological generation, efficiency and innovation*

These experiments demonstrated the creative potential of a multi-criteria optimization tool for assisting decision-making in the sketching phase, designed to explore varied morphological solutions. Although the pre-established morphogenetic model makes it impossible to interact with a free formal composition, which can impede creativity, EcoGen is an interesting tool for creativity, once the users retain the freedom to hierarchize information (notably criteria). Furthermore, the abstraction of this formal model is open to creative interpretation because it leaves users free to perceive forms in a stack of potentially misshapen blocks. Some students who have used EcoGen have mentioned the curved forms (wave, winding path, turning thread, etc.) in proposals made of blocks, thereby regaining their function of a creative architect (Figures 5.13, 5.14 and 5.15). This prompted Hervé Lequay, scientific manager of MAP-Aria, who led the project, to say: "*I don't think students confuse EcoGen's voxel approach, which is, for them, a method like any other of producing an initial morphological sketch, with a materialization of the architectural object, where they give body and reality to forms, surfaces, the embodied space. The 'stacked boxes' vocabulary can be an assumed choice, but an architect will never stop at this phase if he does not qualify the walls and internal spaces*".

Analysis of the data collected through the experiments also shows that the design assisted by EcoGen is performed from the form towards efficiency. If, at first sight, efficiency could be a decision-making criterion, making it possible to retain or remove the form in question, the reality of the activity is more complex and analysis of the process of form choice reveals three typical stages. First of all, the designer identifies a programmatic constraint compatible with the tool's formal proposals. In the second phase, these are interpreted and the designer builds a knowledge base connecting form and efficiency. Thus, morphological archetypes, even eco-models, are identified by the designers, and these formal configurations become hallmarks to be preserved over the generations. The third selection stage is a hierarchization of efficiency criteria, which remains subjective and dictates the choices and the view of the designers. The creative activity of the designer is therefore based on establishing a link between programmatic constraints, efficiency levels and formal solutions.

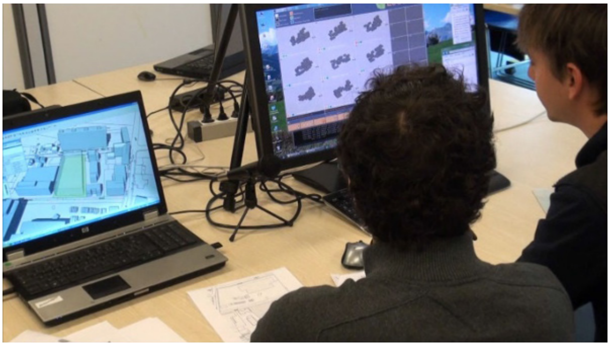

Figure 5.15. *Collaborative work on EcoGen1 in 2012*

Finally, feedback shows that trust in the proposals made by the EcoGen program contributes to a creative freedom that other assistance or *a posteriori* control tools do not allow for. Here, the designers worked on exploratory activities of seeking solutions and understanding interactions. The tool is used as an idea generator, with the bioclimatic or environmental efficiencies displayed remaining as the driving parameters. Furthermore, the morphological forerunners generated become supports for mediation between several designers, allowing for collaboration and objectification of intentions. The value of the solutions generated and the necessary critical distance must, however, remain conditions of design activity. Therefore, although the tool facilitates convergence and reasoned decision-making, it must guide them by means of stimulating discussions, allowing for comparisons, combinations and confrontations.

5.10.4. *Potential targets, dissemination and training in professional environments*

Software tools such as EcoGen, in which the innovative and creative dimension is not disconnected from the consideration of parameters and efficiency criteria, are precursors of sophisticated solutions that will very soon be available to architects. Through their interface, they will also provide additional support for communication between the architect and his/her collaborators. For example, the preferred criteria and typologies can be combined to make selections and architectural choices in real time within a real dialogue, especially when very different forms can quickly be obtained and visualized.

Furthermore, when used appropriately, EcoGen2 can be a vast help in associating technology with design, a key aim in the current context of sustainable development. Indeed, it very early on takes into account technical considerations with which the architect struggles, firstly because his knowledge in these fields is limited and also because working with a professional from each specialism makes the design process longer and more complicated.

After five years of R&D, which have led, among other things, to very quick execution, EcoGen2 can now be integrated into architectural design training at architecture schools, initial or continuous, in the framework of project learning or sciences and techniques for architecture (thermal, lighting engineering). Teaching of architectural project design is often disconnected from theoretical classes on methods and tools of energy and environmental assessment of structures. Extensive training in eco-friendly techniques and strategies is often difficult due to a lack of tools appropriate to the level of knowledge and availability of students. Software programs such as EcoGen seem to directly fulfill this role of early awareness of the challenges of eco-efficiency in building and the consequences of project choices in the upstream phases. They are therefore an important part of training centered on the questions of use, atmosphere and architectural and urban quality.

However, EcoGen’s main target is project managers and architecture firms. It can help them to more effectively and quickly control the efficiencies of buildings, and to discuss more productively with project managers and design offices. The latter may be interested in a global approach to environmental assessment in the sketching phase.

Finally, collaboration with architecture firms and other professionals in living environment planning (town planners, design offices) must make it possible to test the tool in operational situations and to improve its use by and availability to training bodies. This phase includes several aspects: assessing the extent of the preliminary knowledge required for effective mobilization of the tool’s capacities, and assessing the consequences of generative tools on user behavior and the project strategies employed.

6

Bio-inspired Perspectives

In the field of architecture, studying the links between eco-design, biomimicry and creativity now seems key. However, other bio-inspired perspectives are possible. For example, in artificial evolution, research teams have been interested for years in proteomic algorithmic and second-order approaches, which have not yet reached the fields of design. More specifically, structuralist approaches based on self-organization ought to be explored. Coevolutionary approaches between a generative software program and an architect sketching out his project are also emerging issues in architectural design. Finally, longer-term studies can be carried out to find other ways to interact with the drivers of morphogenesis and assessment, which would make it possible, for example, to look for solutions based on project sketches or plans. To achieve this, other generative models must be envisaged, notably supported by *deep learning* and adapted interfaces, which replace human thought and learning within the decision-making process.

6.1. Biomimicry issues in architecture

> "*Learn from nature: that is where our future lies*". (attributed to Leonardo da Vinci)

> "*What we have to learn from nature is to understand its technology*". (Rachel Armstrong [AND 13])

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

6.1.1. *The genesis of bio-inspiration in architecture*

> "*The idea of biological architecture does not date from the 2000s, or even from the initial ecological awareness of the 1970s [...]. The phenomenon existed throughout the 18th century and culminated at the turn of the 19th, when biology became established as an original science, based on its methods [...]. Finally, for the whole of the 20th century, the concepts of cell biology took over, and their architectural uses were manifold: from Le Corbusier's 'hygienist urbanism' to Frederick Kiesler's 'biotechnical surrealism'. However, although the knowledge of living things and its role in architecture should not be reduced to merely the modern history of biology, the influence of biology on architecture in the 21st century must also not be underestimated [...] The work of the art historian George Hersey (1999) on what he called 'architecture's biological roots' does not hesitate to make biology a universal key to all analogies [...]. In terms of seeking forms, ideas or principles, in terms of operational vocabulary, concepts or images, biology is presented as a modern and inexhaustible source, and certainly one of the main references for many architects*". [CHU 12]

In the major transition between the industrial age and the ecological age, a 2007 report from the French senate called biomimicry "*one of the toolboxes of the fourth industrial revolution*". Many paths are yet to be explored in the morphogenesis of living forms and the constructive and conceptual analogies that we can make with architecture. Furthermore, for generative eco-design, the current nascent research should lead to robust methodological approaches and extensive, multi-scale solution databases that can be used from the sketching phase. With this in mind, the first methods developed by researchers to help architects with biomimicry design can be interpreted as a positive sign (section 6.1.3).

6.1.2. *Biomimetic architecture: towards a rebirth of form?*

If nature is an uncontested source of inspiration for mankind, how should we view the design of architectural forms in the age of fashionable biomimicry and the more laborious progress of knowledge on the biogenesis of living things? To what extent is it possible to be inspired by natural systems and to apply them to architecture or architectural design? How can we use biomimicry to design more efficient structures or envelopes, or to produce passive energy for our buildings?

Let us begin by identifying four stages in time:

1) *Bio-inspiration*, which has more or less always existed (an idea is "stolen" from nature: airplane wings inspired by birds' wings, for example). In terms of seeking forms, ideas, principles or concepts, biology is presented as a model, an inexhaustible source and a reference for many architects.

2) The *bioclimatic architecture* of the 1970s–1990s, with the integration into the natural environment and varyingly successful attempts to use external flows of energy (wind, light, heat) and matter (earth, water).

3) *Biomorphism* (simple "copy and pasting" of a form or process, without prior scientific investigation), very fashionable since 1990, but often destabilizing. The attraction of biomorphic architecture is initially explained by the presence of soft, organic, visually pleasant, reassuring forms, promoting imagination or strangeness, and, of course, modern forms, with bold, futuristic and even ecological appearances. In this first stage, for lack of a complete and coherent view of the morphogenetic mechanisms at work in nature (we will have to wait a while longer, believe me), we use only its morphological abundance, on certain scales.

However, biomorphism is only rarely accompanied by an overall scientific approach, and has nothing to do with eco-design. We are still at the stage of formal inspiration and esthetic emotion of a project that seems innovative, but may be technically poor, expensive, or even environmentally unfriendly. We admire the author, the "futurist, visionary architect", for the novelty of the form or for his technical prowess. The example of very tall "green" towers demonstrates this frame of mind, where towns are now in competition and care more for their image than for the well-being of their inhabitants [SAL 07]. I am always critical of both architects who are skilled in "form for form's sake", promoting an esthetic that often has no meaning and is expensive, not very eco-friendly and barely functional, and radical functionalists who have lost their sense of esthetics.

4) *The biomimetic approach,* intrinsically inter- and cross-disciplinary, goes much further and has a scientific and sustainable[1] foundation[2]. It brings together a wide community of researchers who are fascinated by the ingenuity of living things and are involved, among other things, in energy transition. "*It is a scientific and philosophical approach that recognizes nature as an expert in sustainable development for more than three billion years of the evolution of living things. Nature has already solved the problems with which we are confronted. Animals, plants and microbes are accomplished engineers*" [BEN 97]. The approach pioneered by the ecologist Janine Benyus has flourished for the last 20 years. It involves finding inspiration in nature in order to innovate and attempt to resolve some current technological and environmental challenges and, in time, to work towards making all human activities more sustainable and harmonious.

There are still few buildings whose design and functioning have been guided by an overall biomimetic approach. These are mainly symbolic buildings, created by ambitious architects and pioneers in the field. For example, the architect Vincent Callebaut is trying to refresh his practice of eco-design, inspired by biomorphism (intelligence of natural forms), bionics (intelligence of structures of living things and materials) and biomimicry [CAL 08]. The aim of this new architectural practice (called *Archibiotic*) is to construct metabolic, autonomous, positive-energy buildings, in symbiosis with their environment, recycling their own waste. The architect Michael Pawlyn highlights three types of action to be carried out, inspired by solutions that have been tried and tested by nature: radically increasing the effectiveness of our resource management, moving from linear and polluting economics to cyclical economics, and using solar energy in massive quantities [PAW 11].

6.1.3. *Methodologies and findings*

In an eco-design approach, "*biomimicry is a tool that supplements our technical, architectural and constructive knowledge to lend a sustainable and responsible dimension to our design methods [...]. The biomimetic approach has great potential for architecture, from which many sustainable*

1 www.biomimicry.net.
2 www.asknature.org.

constructions and innovations have emerged. It is the result of cooperation between architects, biologists, biomimics and engineers" [CRU 16].

There are two coexisting approaches to biomimicry:

– from biology to technology (solution-based): spontaneous selection of an element of the living being that has interesting properties, with the aim of finding an industrial or architectural application for it;

– from technology to biology (problem-based): we look for a solution to one of mankind's technological or functional problems in nature.

For building and architecture needs, "*biomimicry research is turning towards multi-regulation systems. However, today's classical architecture is still following the idea that an element is designed for a function. For example, facades are made up of different layered materials that each perform a unique task (ventilation, thermal insulation, vapor barrier, acoustic insulation). This design method challenges the natural principles of systems of multi-functional elements, dynamically interlinked and adapted to temporal variations in climate conditions*" [CRU 16].

Biomimicry can be integrated into architecture on three levels: forms, materials and ecosystems, the latter two inspired by construction processes involving recycling and regeneration (the ESA methodology of Maibritt Pedersen Zari [PED 12]), while the first is devoted to the energy optimization of the building's envelopes. To this end, the diagrammatic *BioGen* method developed by Lidia Badarnah [BAD 12, BAD 15] helps architects and engineers to design multi-functional, adaptable envelopes and facades, which behave like living organisms. Taking into account the four fundamental flows – water, air, heat and light – the method helps create transitive envelopes that resolve the challenges of multi-regulation for a given climate.

In terms of materials, it is useful to remember that living things use non-toxic, 100% recyclable raw materials, found nearby, and that they arrange them in successive layers in the surrounding temperature to form their habitat. Finally, in an ecosystem, what is waste for some is raw materials for others. And this mutual dependence is still more fundamental: it is a system whose parts are not interchangeable, like the pieces of a mechanical object. There are life logics of groups and species in ecosystems, from which we must draw inspiration in order to learn to design differently and construct sustainably, in a simpler way.

It is not about systematically looking for analogies on a large scale but mechanism by mechanism and level by level, justified by the fact that, until now, the organicity of a building being still fairly artificial, we can still approach its components with more or less independent techniques.

In a short amount of time, the number of global publications on biomimicry and its applications has surpassed the linear growth stage. This trend will certainly continue and should make it possible, in the medium term:

– to promote the energy efficiency of constructions and their envelopes (first principle of economy in nature);

– to obtain more efficient, gentle, agreeable forms and structures, even if they may sometimes seem radically different from those proposed by classical or modern architecture;

– to gradually move away from economics of linear growth based on fossil and/or distant resources, working as much as possible with local products, and using as little energy as possible for transformations. "*The architecture of the future will employ all available materials in their proper place. Using exclusive high-tech materials can only define a restricted architecture*" [SAL 07];

– to gradually abandon polluting solutions and integrate recycling into design;

– to work to obtain metabolic and non-toxic materials, facilitating: weight loss for structures, self-ventilation, heat exchanges, environmental adaptation, self-repair, saving and storage of water, harnessing, local production and transfer of energy;

– to design envelopes that are "living" (breathing, filtering, self-concealing, luminescent [FER 14], heating, cooling [GUT 14], etc.) and reactive [PER 12, LLA 14], for example to climate change;

– to help solve cross-cutting problems, such as the management of water and energy, thermoregulation, the construction of efficient and light structures and the regeneration of the ecosystems implemented [PED 12];

– to review in depth our hyper-technological design of life and artificialization of living things, which goes hand-in-hand with it on all levels.

6.1.4. *Conclusion*

A fascinating, almost enchanting universe lies open to anyone who contemplates and studies the natural and living worlds, from the macroscopic to the microscopic. We understand its attraction for architects, designers of habitats, forms and living spaces. This partly justifies the current fashion for biomimicry, as long as it does not merely copy-and-paste nature. We must fully enter into the intelligence of living worlds to grasp their fundamental principles, and those that can then be carried over to architecture. This is the subject of Alexander's last book, *The Nature of Order* [ALE 02, ALE 04, ALE 05], which is highly recommended reading.

6.2. A return to the theories of evolution

6.2.1. *A brief history of natural evolution*

The evolution of living things is a scientifically recognized fact, although we continue to use the word theory, which denotes hypothesized explanations. Two centuries of research have shown that all living organisms are united by links of ancestry, proven by the observation and analysis of a very large number of living and fossil species, and, over the last 20 years, the comparison of their genetic heritages [COL 10]. This can be based only extremely rarely on experiments (scarcely reproducible, given the timescales involved), although there are "*in-vivo*" areas in some parts of the world, where researchers are able to observe it. More recently, computing models produced in the context of artificial evolution have helped us to understand some explanatory mechanisms on the genetic level (section 6.3.4).

In the scientific community, three historical methods are distinguished for explaining the phenomenon of biological evolution: Darwinian evolution (we now speak of neo-Darwinism, encompassing genetics, which was unknown at Darwin's time, around 1850), Lamarckian evolution [LAM 09] and Baldwinian evolution [BAL 96].

Lamarck was the forerunner of the theories of evolution [LAM 09]: he suggested that an individual could directly transmit the characteristics acquired throughout its lifetime to its offspring, and thus quickly adapt to its environment. This concept of feedback from the phenotype to the genotype, known as the “inheritance of acquired characteristics mechanism”, has been proved generally wrong, with a few exceptions.

The neo-Darwinian theory is the best known, because it offers a plausible explanation for many evolutionary behaviors observed in the world of living organisms. In 1859, Darwin, who was, above all, an excellent observer of nature, laid out all known living species over a large time-scale in a tree of life formed of inter-related organisms. The neo-Darwinian mechanism is based on the convergence of two phenomena: natural selection imposed by the environment – the individuals that are best adapted to their environment reproduce more efficiently and survive – and non-guided variations of “the genetic material of species” (explanation after Darwin). Nature therefore uses chance and natural selection to gradually make species evolve, even if Darwin had already recognized the shortage of observable transitory forms. These are also the two principles that underlie the first evolutionary algorithms (1970).

Finally, the later Baldwinian approach [BAL 96] is a way of reconciling Lamarckism and Darwinism, without using Lamarck’s (unproven) hypothesis, which states that learning directly affects the genome. For Baldwin [BAL 96], selection also depends on experience (individually acquired characteristics reinforcing or replacing similar hereditary characteristics).

It took a century of work after the publication of Darwin’s theory to discover the genomic basis of evolution. DNA, a remarkable macromolecule composed of sequences of pairs of bases called nucleotides (four possible letters: A, C, G and T), with the capacity for self-repair, was discovered by Crick and Watson in 1953. DNA molecules are themselves wrapped up in chromosomes within the nucleus of each cell. A DNA “instruction” is called a gene, and it can be made up of hundreds or thousands of nucleotides, whose determination is empirical. The genome is not a linear sequence of independent genes. In living organisms, genes form a highly connected, complex network (pleiotropy).

DNA is not an explicit morphological implementation plan, but the code that enables the proteins that make up the cells (and therefore organs, metabolic networks, etc.) of a living organism to be manufactured. Proteins are made directly by decoding one or more genes from the partial replication of DNA fragments by cytoplasm ribosomes.

6.2.2. *What's new since Darwin?*

> "*Science is always a series of refutable proposals. Anything that cannot be refuted belongs to the realm of magic or mystery, not science*" (Ilya Prigogine, quoted in [HEU 98]).

In nature, the adaptation of living species to their environment is a proven fact, but no one has ever demonstrated that a form appears when the function becomes necessary, through a series of trials and errors, based on random genetic mutations. The historical Darwinian explanation now seems insufficient for many researchers, for whom evolution is mainly based on the organization of the living complexity. Today, the study of evolution takes in four major interacting scientific fields: paleontology, molecular biology, genomics and the theory of complexity (which has advanced considerably through the study of living organisms).

Biologists and geneticists are only in the early stages of understanding the mechanisms of the morphogenesis of living organisms, i.e. the passage (Figure 6.2) of the genotype (DNA code) to the proteome (cellular proteins), and then to the phenotype (the living organism). The studies of the geneticist Andras Paldi [PAL 09] especially question the dominant theory of genetic determinism. Notably studying cloning, he suggests a form of epigenetic inheritance in which all the proteins and micro-organelles of the cytoplasm (which ensures metabolic and structural properties) contribute to morphogenesis as much as the DNA genes do.

Other approaches, called "structuralist", focus on classifying emerging forms using the laws of chemistry and physics. We will cite the works of the geneticist and biochemist Michael Denton on the forms of proteins [DEN 02]: although there are tens of millions of proteins, they take just over one thousand basic forms, they are always grouped in morphologically limited structures. The Nobel laureate in medicine Christian de Duve has demonstrated that the laws of biochemistry produce constraints so strict that mutational hazard is channeled [DE 05]. Simon Conway-Morris, one of the greatest living paleontologists, has demonstrated that within evolution, many paths produce almost identical results, which he calls "convergences" towards biological forms in an ultimately fairly limited number [CON 09]. This approach postulates the existence of something similar to attractors in mathematics, through which evolutionary paths are channeled towards stable functional forms. These structuralist analyses produce a view according to which "*natural selection exists on many levels in nature, but is not the only or the main driver of evolution. In living organisms, structure – and therefore form – is more important than function (usefulness of an organ). […] This tends to indicate the existence of internal logics in the individual development of each organism*" [STA 09].

6.3. New morphogenetic approaches

6.3.1. *Urban forms and pleiotropy*

An initial example of a bio-inspired morphogenetic approach is a study carried out between 2001 and 2003 at MAP-Aria, the aim of which was to understand the internal consistency of urban forms by detecting their internal similarities. Achieving this required finding an approximate mathematical model (analysis phase), in order to automatically produce new urban morphologies (synthesis phase). The researchers intuitively used a method of fractal image compression to code, using an "iterated function system" (IFS), the "urban footprint + height" pair, transformed into an image.

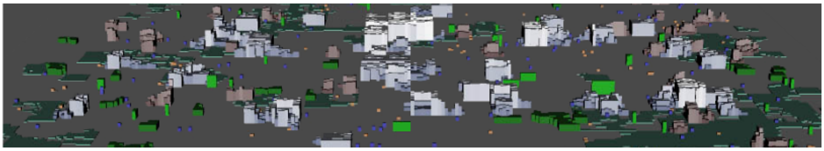

Figure 6.1. *Synthesis of a self-similar urban fabric via an IFS*

One genetic formalism has consisted of considering the IFS of an image as a chromosome whose genes represent local self-similar transformations, and then using crossover operators. As well as using the IFS (genotype) on the urban plan (phenotype), the morphological information is distributed pleiotropically across all the genes. Due to their fractal principle, IFSs have the advantage of enabling both global and local forms to be analyzed and synthesized. Therefore, on the scale of buildings, we can observe the morphological details resulting from the self-similarities detected on more global levels (Figure 6.1). For more information, see the synthesis article [MAR 05].

6.3.2. *Complexity and evolution of built environments*

Architecture, just like the construction on which it is based, is not complex, even if some morphological and organizational aspects might lead us to describe it as such. From a morphogenetic point of view, there is no global principle of organicity, nor self-organization, nor evolution (other than in the method of copying and transformation of tried and tested models or solutions), although like a living organism, every structure has a hierarchy of forms and functions.

A building does not evolve in the Darwinian sense, and it does not reproduce. There is no principle of variation or selection through competition (except, perhaps, in an architectural competition stage!). It evolves very little during its life cycle and can retain its errors for a long time before being fixed, renovated, or even abandoned, and ultimately simply destroyed. It may also inspire later generations of architects, and, in this sense, have descendants, in terms of the method of production through copy and variation without explicit DNA.

If there is evolution, it is found on certain scales of a town (self-organization), or even in construction, design and planning practices. Thus, the phases of building and neighborhood design are generally complex and evolutionary (technically, cognitively, historically, etc.). The pyramid of complexity “cell → tissue → organ → limb → body → society → ecosystem” may be transposed onto the urban environment, and partly onto the building, without a principle of morphogenesis, as in nature.

There is no urban DNA in the genetic sense (coding pattern, integrated memory), just as one part of the building is not intrinsically linked to another by a genome (the approach described in section 6.3.1 deals only with a morphological code, not architecturally-guided morphogenesis). However, from a purely functional point of view, the metabolic analogy of the body seems fairly appropriate: they must provide energy and nutrients for all their parts (distribution mechanism constrained by the topology of the body) and remove their waste.

In architecture, we do not use a cellular approach (micro) with copying and differentiation at all, even on the most basic construction level. We initially deal with a set of components on the meso or macro level, with constructive principles and rules of assembly and organization. The plan of all the objects produced is not coded in a cellular nucleus. It is causal (decided and scheduled), and its logics are, above all, external: those of the designer and the manufacturing and implementation techniques, always able to be improved and constantly evolving. As for that of a town or neighborhood, it is the result of self-organization and emergence just as much as of precise planning.

We propose that these logics and rules should be considered potential entries in a new morphogenetic system: they could be stored as "non-coding material" in a chromosome dedicated for this purpose and ultimately used in a buffer zone between genotype and phenotype, like the proteome (section 6.3.4).

6.3.3. *Evolutionary creativity*

In artificial evolution, we are almost obliged to define objectives to be reached, as soon as we become interested in optimizing measures or efficiencies in the phenotypical space. In the evolution of biological systems, meanwhile, nature is unaware of what we call efficiencies, surprising as that may seem. Viable organisms are content to live and produce offspring. Of course, they all evolve (individuals, species, ecosystems), each following its own rhythm. However, this evolution can be studied in other terms than that of optimization. And the "Darwinian" survival of "the fittest" individuals alone cannot explain the wealth of forms produced in nature. Hence the question: what principles are hiding behind natural morphogenesis?

In 2001, Gero asked the question: "*can an algorithm be creative?*" [GER 01]. For 40 years, the practice of artificial evolution in many disciplinary fields has not challenged the relevance or efficiency of the algorithms inspired by neo-Darwinism for problems related to optimization. They correspond to natural microevolution, i.e. adaptation. Processes of morphogenesis use the phases of optimization, but these phases are almost certainly not enough to produce original forms, and we must introduce a likely method of producing an analog of macroevolutions in genetics.

I am entirely convinced, having read the conclusions of eminent researchers such as Pierre-Yves Oudeyer, that Darwinism is not a principle of morphogenesis [OUD 13]. We must distinguish – beyond simply using evolutionary algorithms – what comes from morphogenesis and what comes from adaptation. Without denying that the two are linked, it is rare for an optimization process of an initial form to produce a radically different form. A "qualitative leap" is rare if morphogenesis has not been designed for this purpose. Yet, without a strong structural approach, I do not think that we can innovate and boost creativity in the field of morphogenesis, particularly in generative architecture. However, few researchers have worked on these subjects.

Finally, chance creates nothing in itself, but channeling it into evolutionary and/or structuring algorithms makes it possible to access sets of optimized solutions via multiple paths, and, in doing so, to stimulate the creativity of the user, sometimes leading to serendipity.

6.3.4. *Structural or second-order evolution*

This section is a brief summary of texts by Beslon [BES 08a] and Lefort-Mathivet [LEF 07].

We talk about second-order evolution (or indirect selection) when individuals are selected not only for their adaptation to an environment but also for their evolvability, i.e. their capacity to ultimately evolve "better". In nature, evolutionary mechanisms have structured the genome, leaving it some freedom in the coding and placement of genes along the chromosomes. And researchers have shown that a dynamic gene structure facilitates this second-order evolution (evolution of evolution).

AEVOL is one of the first *in silico* models of experimental evolution (or artificial evolution), developed by the Beagle team at LIRIS in Lyon[3]. Organisms are described in three levels of organization (Figure 6.2): the genome (double-stranded circular sequence), the proteome (collection of functional elements translated from gene sequences) and the phenotype (functional capacities).

The authors have demonstrated that second-order selection is at work in the algorithm, making it possible to shape genomes by altering the sizes of the non-coding zones and the number and order of genes (unusual with conventional GAs). Therefore, as genetic structure is variable, we can use more varied mutational mechanisms than those that appear within normal GAs: rearrangements. The evolution of individuals is accompanied by profound mutations in the structure of their genome (number of genes, variations in genome size, size of non-coding sequences), which move through phases of expansion, then compression, and finally stabilization, with the improvement of efficiencies.

Although such a mechanism is initially very interesting in artificial evolution, the structure of AEs generally prohibits this, because the evolutionary processes are fixed. In 2007, Guillaume Beslon and Virginie Lefort proposed, for optimization purposes, the RBF-Gene algorithm [LEF 07], using the evolutionary characteristics observed in AEVOL. Like AEVOL, it has an intermediary level between the phenotype and the genotype: the proteome, a set of "proteins" that make it possible to vary the structure of the genome without altering the phenotype, in the knowledge that these variations will influence future reproduction. The AE can then adapt its complexity to respond to environmental conditions.

6.3.5. *A proposal for bio-inspired architectural genetics*

Today, researchers must reflect on a more global approach to structuralism [ROU 10] – particularly relevant in the sketching phase – having spent several decades studying the adaptation of objects to the requirements of the efficiencies chosen by the user.

3 liris.cnrs.fr/equipes?id=64.

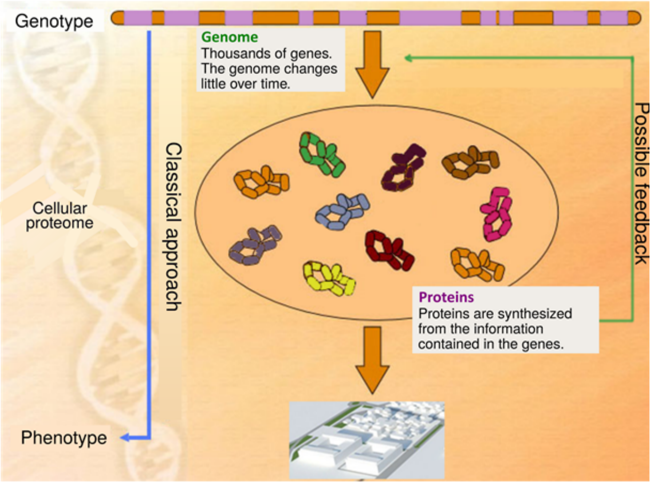

Figure 6.2. *Classic and proteomic genetic approaches (adapted from Lefort-Mathivet [LEF 07]). For a color version of the figure, see www.iste.co.uk/marsault/architecture.zip*

Since the study that we conducted in 2003 with the IFS (section 6.3.1), we have wanted to construct a bio-inspired architectural morphogenesis. In this context, we now want to challenge structuralist formalism as a resource for promoting, among other things, prior morphological proposals not limited to predefined architectural models. Exploring types of architectone other than those based on voxels is therefore one of the aims of this research.

To extend the morphogenesis capacities of a generative tool, one promising avenue for research is the concept of the proteome [LEF 07], which consists of separating the substrate of evolution into three fields, as in biology: the genome, the proteins produced by reading the genes, and the cells/tissues/organs/objects produced with these proteins. This could be broken down for a building as follows:

– the proteins represent materiality: elements, materials, binders, etc.;

– the DNA contains the genes of the project (the coding elements of an intelligent selection of these proteins), and also the knowledge accumulated throughout history, which evolves slowly (construction processes, rules of assembly, procedural models, architectural techniques, design methods, etc.), as an analogy with non-coding chromosome sequences in biology;

– and, finally, the phenotype: a solution that can emerge from interactions between the genome and the proteome (Figure 6.2). We must emphasize the complex nature of these interactions, whose blueprint is far from a linear decoding of information carried by the "project genes" (feedback). An exciting construction!

6.4. Assisted creativity, coevolution and design of learning systems

6.4.1. *Ergonomics and design of coevolutionary and learning systems*

Darwinian natural selection works very well for the adaptation of species to many types of constraint, but we often forget cooperation, which is omnipresent in nature, built on bonds of coevolution between species and groups of species. Bio-inspiration encourages us to think about design support software systems, with less optimization and better compatibility, which involve coevolving the architect/generative engine pair.

Beyond the possible evolutions of EcoGen, which aim to enable the user to interact in many ways with the population of generated objects, there is a high demand for tools that are highly adapted to the design methods of architects, responding to ergonomic and cognitive challenges that are essential if they are to be acceptable in an operational situation. The methods are certainly very varied [CHU 12] and, although considerable efforts have been made on the level of the interfaces, the prototypes being developed in laboratories are far from providing an interactive multi-criteria diagnosis (even a very approximate one) from a project sketch or plan (e.g. *Minos*). Research is aiming to get there but there are still major scientific obstacles in the way, notably in artificial intelligence (e.g. real-time recognition of gestures or drawing by hand and its interpretation).

Building on the record of past years in order to better understand efficient eco-design strategies, we might envisage autonomization/automatization of the design process, no longer based on rules outside human thinking (e.g. Darwinian selection), but on learning abilities that are closer to the workings of the human brain. This is why deep learning[4] appeals to us, more in terms of designing learning systems for architecture than of the technique in itself.

The powerful software environments and deep learning equipment that have emerged over the last 2 years (such as AlphaGo[5] and TensorFlow[6] from Google and the DGX-1 server from Nvidia[7]) may soon facilitate a radical reworking of our approach to decision-making support. The principles of learning, solution seeking and optimization on which EcoGen is based will be reassessed through the prism of these new techniques, provided that we have adequate foundations for learning, which is the challenge! We must produce a network with a large number of bodies so that it can learn enough.

Otherwise, Bayesian networks may be an alternative if we want to learn about the probabilistic relationships between cause and effect, so as to better design and anticipate the pathologies of the building, for example [HAN 16].

6.4.2. *Computational resonance and artificial creativity*

This research was conducted by Joaquim Silvestre at Keio University, under the supervision of Professor Ikeda and in collaboration with Professor François Guéna from MAP-Maacc. The aim was to study a “computational object”, where user, hardware, software and architectural production interact to identify the artificial intelligence or creativity known as *computational resonance*. Many experiments and observations have been conducted in various contexts and using various tools. This body of work has enabled various parameters characterizing computational resonances to be identified. The results have led to the testing of an original use of convolution networks, which are widely used to recognize forms in images but can also produce images from combinations of various categories [SIL 16], and stimulate creativity at the beginning of the design process.

4 deeplearning.net.
5 deepmind.com/research/alphago.
6 www.tensorflow.org.
7 www.nvidia.com.

Conclusion

We have reached the end of our journey. A series of general presentations and techniques have provided a broad view of generative eco-design and suggested avenues for research and reflection, even in fields that may seem somewhat removed from the original topic. We have mainly shown that, in the sketching phases, researchers put a lot of effort into energy-related aspects, with a major impact on the overall cost of the construction and functioning of buildings. The environmental aspect – particularly lifecycle analysis and, recently, low carbon – is still treated as the poor relation. We have tried to find some reasons for this. However, this should not last too long and, sooner or later, as with BIM, methods and tools will make it possible to integrate it more effectively into current practices for designing new structures and renovating tens of millions of buildings.

For now, I would like to end with a less technical look at some aspects that have until now been deliberately ignored in this book, relating, among other things, to the consideration of complexity in the ways we design, behave and interact with the world around us. I am well aware that I have often strayed some distance from the original topic of this book, which is certainly still emerging, taking the reader down unusual paths. But I believe it is necessary, especially today, when we claim to place mankind at the center of the architectural project, to bring together external disciplinary contributions in order to attempt to achieve a form of consistency, even beyond trendy global thinking, within the natural worlds that we observe and the technical and cultural systems that we build.

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

As always, we must take the time to inform ourselves, to read and to allow our intuition to sketch paths that we would not have envisaged through linear thinking. This may take time. It is essential!

Architecture and complexity

Salingaros reminds us that "*if science has revealed anything in the last 100 years, it is the coherent character of the universe, demonstrated by its ordained complexity. Natural morphogenesis unites matter, establishing multiple connections on different scales and increasing the system's overall coherence*" [SAL 09]. We can no longer ignore all of this! However, it shows that the majority of major theoretical concerns, such as the hierarchical complexity of the architectural form and the algorithms that generate adaptive structures, are almost entirely absent from current architectural thinking and teaching. They are even deliberately circumvented or hijacked in favor of a destructuring of form (inspired by deconstructivism), radically opposed to the self-organization of complex systems, a process that builds internal connectivity networks.

Furthermore, "*there is a basic confusion in contemporary architectural discourse between processes and final appearances. Just because something is created on a computer screen does not validate it, regardless of the complexity of the program used to produce it. One has to ask: what are the generative processes that produced this form, and are they relevant to architecture?*" [SAL 09].

Most architects use generative programs, but, for now, few seem to understand Christopher Alexander's "fifteen fundamental properties", which generate "living" and harmonious structures [ALE 02, ALE 04, ALE 05]. Some of them, who have the ability and the resources, supported by research and development teams, try to program environments based on similar properties, such as *Generative Codes*[1]. The generative approach based on eco-models, which we suggested examining in more detail in section 5.1.1, should also move in this direction.

1 www.patterns.architexturez.net.

Architecture and sensitivity

The eco-design of built environments has meaning only if it enables humans to live in better conditions, so that they can thrive. The first attribute of an architectural work, as Frank Lloyd Wright said, is to create a feeling of well-being in interior and exterior spaces. Yet, to supplement the previous section, "*the term architecture denotes the relationships between the various elements of a system and the specific way in which they are integrated into a coherent series, upon which we feel the fulfillment of a feeling of life*" [SAL 09].

Few people have read Alexander's extensive overview, *The Nature of Order* [ALE 02, ALE 04, ALE 05]. Well before the first works in sensory neuropsychology appeared – like those of Erich Fromm, the real father of the biophilia theory [FRO 64] – the author understood the existence of links between our "neuro-wired" sensitivity and the evolution of mineral and living forms in nature. On a similar subject, based on the perception, experience and artistic sensitivity of people, Alain de Botton provides in *Architecture du bonheur* an extensive biophilic reflection on the importance of buildings and items of furniture promoting feelings of fulfillment in the people who live there, possess them or are regularly near them [DEB 06]. This knowledge, which seems embedded in the innate connective structures of our brains, makes it possible to explain how we feel in the face of some architectural forms or in certain spaces, ranging from feelings of well-being to stress, disorientation, and even deeper psycho-sensory problems, depending on the case and the people. A word to the wise…

Contemporary forms and challenges

Finally, controlling form has never been an objective suited to the challenges of the human habitat. At the beginning of the 21st Century, we need habitable places with a low environmental impact. In light of these priority issues, the question of form may seem marginal. Of course, it cannot be so for architects, and still less for those who support the artistic side of the profession. However, it presents endlessly recurring challenges with the objects from digital design and their production method [KOL 10], particularly their constructability and psycho-sensory impact. Finally, the main thing is to know whether the question of form is detrimental to the others, and whether architects can preserve and construct organic links between their products and their immediate environments.

Complexity and human behavior

At the dawn of the 21st Century, technique, or rather technoscience, took on a major, not to say hegemonic, role in our daily lives. My aim here is not to question this fact, but to highlight some of its limitations and propose some counterbalances.

First, researchers are unanimous: in the immediate future, and even in the medium term, we have neither the knowledge, the methodological tools, the models nor the simulation power to approach complex anthropogenic systems in their entirety, so as to provide real software programs to support decision-making. Certainly, there has been a lot of research into these questions all over the world, passionate researchers, vast amounts of resources and partial successes. However, interdisciplinary, and even cross-disciplinary, work is not yet sufficiently developed, despite the encouragement of project calls and the efforts of some scientific research bodies to review the compartmentalization of university scientific fields. And, in any case, we come up against limitations and major scientific, technical and human obstacles, and will continue to do so for the foreseeable future.

Furthermore, the problems that mankind has always faced are never only technical, economic and political. They are the result of habits and varyingly free decisions, repeated millions of times, which structure and shape our consumption habits and social lives (this is the *bottom-up* component of complexity). Human behavior is certainly not dissociated from technical behavior, but it needs to be taken into account very seriously, beyond the capacity of models and simulations. The desire to educate mankind to behave better, and to take into account the complexity of the environments in which we live, now seems essential.

Simplicity, restraint and global ecology

Post-industrial society is attempting to reduce the ecological footprint of its activities while maintaining an exceptionally high-quality lifestyle, at the cost of damage to its environment, to which mankind tries to adapt, often through an excess of technological equipment that increases the environmental debt still further, particularly in urban environments and poor countries. Yet we have seen that in nature, complexity expands on a basis of energy minimization, or rather, frugality. There is an increasing need to take this principle into account in social and economic life, and I believe that the vital challenges will oblige us to do so sooner or later, whether we want to or not.

At the same time, "*there is an evident saturation among western populations, committed to a program of growth in whose results they have less and less of a share*" *[COU 10]*. Restraint to counterbalance the excesses of technoscience appears increasingly necessary. *Lifestyle choices with low ecological impact must be proposed and guided, to re-insert human beings into new fabrics of social relationships, and redirect or even cancel the projects with the most negative impact on the lives of vulnerable populations [GAD 09]*.

Is the rural exodus irreversible?

Finally, we will probably see, sooner or later, an inversion of the rural exodus phenomenon, because the very principle of very large towns seems increasingly unsustainable. We welcome the fact that this awareness has made a lot of progress and will surely bring about a revival of the rural world and the emergence of "human-scale" living environments, designed more ecologically (*without fossil energy or pesticides, and only a few vehicles*), and with all the intelligence required to provide their occupants with the most dignified and fulfilling living conditions. The evidence of good environmental behavior and good living, a force of human ecology, will find its purpose in this return to a more natural and peaceful life.

Thus, in all things, it seems to me that we must both find and discover the wisdom of action suited to the challenges of the modern world. "*A global ecology – which considers all aspects of mankind and nature, without opposing or separating them – conveys a simplicity that can be understood by as many people as possible*". You need only read [BÈS 14] to be convinced of it.

Bibliography

Aeraulics and climatology

[BAN 07] BANZHAF E., KINDLER A., HAASE D., "Monitoring, mapping and modeling urban decline: a multi-scale approach for Leipzig", *EARSeL eProceedings*, vol. 6, no. 2, pp. 101–114, 2007.

[CHA 05] CHAU K.W., ANSON M., ZHANG J.P., "4D dynamic construction management and visualization software: 1. Development", *Automation in Construction*, vol. 14, no. 4, pp. 512–524, 2005.

[ELI 06] ELIASSON I., OFFERLE B., GRIMMOND C.S.B. *et al.*, "Wind fields and turbulence statistics in an urban street canyon", *Atmosphere & Environment*, vol. 40, pp. 1–16, 2006.

[FRA 04] FRANKE J., HIRSCH C., JENSEN A.G. *et al.*, "Recommendations on the use of CFD in wind engineering", *Proceedings of the International Conference on Urban Wind Engineering and Building Aerodynamics*, Belgium, 5–7 May 2004.

[GAG 86] GAGGE A.P., FOBELETS A.P., BERGLUND A.P., "A standard predictive index of human response to the thermal environment", *ASHRAE Transactions*, vol. 92, p. 709, 1986.

[HEI 10] HEISELBERG P., PERINO M., "Short-term airing by natural ventilation – implication on IAQ and thermal comfort", *Indoor Air*, vol. 20, pp. 126–140, 2010.

[HUA 12] HUANG Y., MUSY M., CHEN H. *et al.*, "Méthodologies de conception climatique de quartiers urbains pour l'efficacité énergétique des bâtiments", *Revue Références* Commissariat général au développement durable – Direction de la recherche et de l'innovation – Modélisation urbaine: de la représentation au projet, September 2012.

Eco-generative Design for Early Stages of Architecture, First Edition. Xavier Marsault.

[KAL 93] KALKSTEIN L.S., SMOYER K.E., "The impact of climate change on human health: some international implications", *Experientia*, vol. 49, p. 969, 1993.

[MAS 00] MASSON V., "A physically-based scheme for the urban energy budget in atmospheric models", *Boundary-Layer Meteorology*, vol. 94, p. 357, 2000.

[MAS 09/14] MASSON V., VIGUIE V., LEMONSU A. *et al.*, "Modélisation Urbaine et Stratégie d'adaptation au Changement climatique pour Anticiper la Demande et la production Énergétique", projet de recherche MUSCADE, ANR Ville Durable 09-VILL-0003, 2009–2014.

[MAV 14a] MAVROMATIDIS L.E., MAVROMATIDI A., LEQUAY H., "The unbearable lightness of expertness or space creation in the "climate change" era: a theoretical extension of the "constructal law" for building and urban design", *City, Culture and Society*, vol. 5, pp. 21–29, 2014.

[MCQ 05] MCQUISTON F.C., PARKER J.D., SPITLER J.D., *Heating, Ventilating and Air Conditioning Analysis and Design*, 6th ed., Wiley, 2005.

[MOR 15] MORILLE B., LAUZET N., MUSY M., "SOLENE-microclimate: a tool to evaluate envelopes efficiency on energy consumption at district scale", *IBPC 2015: 6th International Building Physics Conference*, *Energy Procedia*, vol. 78, pp. 1165–1170, 2015.

[TAB 09] TABLADA A., DE TROYER F., BLOCKEN B. *et al.*, "On natural ventilation and thermal comfort in compact urban environments-the Old Havana case", *Building and Environment*, vol. 44, pp. 1943–1958, 2009.

[TOM 08] TOMINAGA Y., MOCHIDA A., YOSHIE R. *et al.*, "AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings", *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 96, p. 1749, 2008.

Algorithms, complexity, models

[BES 08a] BESLON G., Apprivoiser la vie: modélisation individu-centrée de systèmes biologiques complexes, HDR, University of Lyon, 2008.

[BOX 60] BOX G.E.P., BEHNKEN D.W., "Some new three level designs for the study of quantitative variables", *Technometrics*, vol. 2, pp. 455–475, 1960.

[BOX 76] BOX G.E.P., "Science and statistics", *Journal of the American Statistical Association*, vol. 71, no. 356, pp. 791–799, 1976.

[CHE 03] CHENG J., MASSER I., “Urban growth pattern modeling: a case study of Wuhan City, PR China”, *Landscape and Urban Planning*, vol. 62, pp. 199–217, 2003.

[DEC 09] DE CRECY F., “Plans d’expériences et de simulations pour les microtechnologies”, *Séminaire du CEA*, 2009.

[DOE 70] DOEHLERT D.H., “Uniform shell designs”, *Applied Statistics*, vol. 19, p. 231, 1970.

[FAI 13] FAIVRE R., “Méta-modélisation par régression paramétrique et non-paramétrique”, Ecole de Physique, Les Houches, 11 April 2013.

[GIE 03] GIELIS J., “A generic geometric transformation that unifies a wide range of natural and abstract shapes”, *American Journal of Botany*, vol. 90, no. 3, 2003.

[GOU 06] GOUPY J., “Les plans d’expérience”, *Revue Modulad*, no. 34, pp. 74–116, 2006.

[HAN 16] HANNACHI-BELKADI N., “Les Réseaux Bayésiens: une solution pour une conception de bâtiments économes en énergie adaptée et/ou adaptable aux différents usagers”, *8èmes Journées Francophones sur les Réseaux Bayésiens et les Modèles Graphiques Probabilistes (JFRB 2016)*, Clermont Ferrand, 27–28 June 2016.

[HEU 98] HEUDIN J.C., *L’évolution au bord du chaos*, Hermès, 1998.

[HOX 16] HOXHA E., JUSSELME T., BRAMBILLA A. *et al.*, “Impact targets as guidelines towards low carbon buildings: preliminary concept”, *PLEA*, Los Angeles, USA, 2016.

[INS 91] INSELBERG A., DIMSDALE B., “Parallel coordinates”, in KLINGER A. (ed.), *Human–Machine Interactive Systems, Languages and Information Systems*, Springer, 1991.

[JAC 11] JACQUES J., “Pratique de l’analyse de sensibilité: comment évaluer l’impact des entrées aléatoires sur la sortie d’un modèle mathématique”, *IRMA 2011*, vol. 71, no. III, Lille, 2011.

[JUS 16] JUSSELME T., COZZA S., HOXHA E. *et al.*, “Towards a pre-design method for low carbon architectural strategies”, *PLEA 2016*, Los Angeles, CA, 2016.

[KIM 03] KIM H.M., MICHELENA N.F., PAPALAMBROS P.Y. *et al.*, “Target cascading in optimal system design”, *Journal of Mechanical Design*, vol. 125, no. 3, pp. 474–480, 2003.

[LIU 06] LIU H., CHEN W., KOKKOLARAS M. *et al.*, “Probabilistic analytical target cascading: a moment matching formulation for multilevel optimization under uncertainty”, *Journal of Mechanical Design*, vol. 128, no. 4, pp. 991–1000, 2006.

[MON 14] MONOD H., “Plans d’expérience pour le criblage et l’analyse de sensibilité”, Ecole de Physique, Les Houches, 6 May 2014.

[MOR 91] MORRIS M.D., “Factorial sampling plans for preliminary computational experiments”, *Technometrics*, vol. 33, pp. 161–174, 1991.

[SIL 16] SILVESTRE J., IKEDA Y., GUENA F., “Artificial imagination of architecture with deep convolutional neural network”, *Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA*, pp. 881–890, 2016.

[SUD 14] SUDRET B., “Polynomial chaos expansions for sensitivity analysis”, Ecole de printemps ASPEN, Les Houches, 9 May 2014.

[TIA 11] TIAN W., DE WILDE P., “Uncertainty and sensitivity analysis of building performance using probabilistic climate projections: a UK case study”, *Automation in Construction*, vol. 20, pp. 1096–1109, 2011.

[VAR 14] VARENNE F., SILBERSTEIN M., DUTREUIL S. *et al.*, *Modéliser & simuler, Epistémologies et pratiques de la modélisation et de la simulation*, vol. 2, Editions Matériologiques, 2014.

Evolutionary algorithms

[ALA 07] ALAYA I., SOLNON C., GHEDIRA K., “Ant colony optimization for multi-objective optimization problems”, *19th IEEE International Conference on Tools with Artificial Intelligence, (ICTAI)*, Greece, 2007. doi: 10.1109/ICTAI.2007.108.

[ANG 09] ANGUS D., WOODWARD C., “Multiple objective ant colony optimisation”, *Swarm Intelligence*, vol. 3, pp. 69–85, 2009.

[CAR 08] CARPENTIER G., Approche computationnelle de l’orchestration musicale, optimisation multicritère sous contraintes de combinaisons instrumentales dans de grandes banques de sons, IRCAM, Thesis, University of Paris VI, 2008.

[COE 02] COELLO C.A., MEZURA-MONTES E., “Constraint-handling in genetic algorithms through the use of dominance-based tournament selection”, *Advanced Engineering Informatics*, vol. 16, pp. 193–203, 2002.

[COE 07] COELLO C.A., VAN VELDHUIZEN D.A., LAMONT G.B., *Evolutionary Algorithms for Solving Multi-Objective Problems*, Kluwer Academic Publishers, 2007.

[DEB 02a] DEB K., AGRAWAL S., PRATAP A. *et al.*, “A fast and elitist multi-objective genetic algorithm: NSGA-II”, *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, 2002.

[DEB 02b] DEB K., An Efficient Constraint Handling Method for Genetic Algorithms, Kanpur Genetic Algorithms Laboratory (KanGAL), Indian Institute of Technology Kanpur, 2002.

[DEB 07] DEB K., SAXENA D.K., On Finding Pareto-Optimal Solutions Through Dimensionality Reduction for Certain Large-Dimensional Multi-Objective Optimization Problems, Kanpur Genetic Algorithms Laboratory (KanGAL), 2007.

[DEB 11] DEB K., Multi-objective optimization using evolutionary algorithms: an introduction, KanGAL Report Number 3, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, 2011.

[EIB 03] EIBEN A.E., SMITH J.E., *Introduction to Evolutionary Computing*, Springer Verlag, 2003.

[ELA 07] ELAOUD S., LOUKIL T., TEGHEM J., “The pareto fitness genetic algorithm: test function study”, *European Journal of Operational Research*, no. 177, pp. 1703–1719, 2007.

[GAI 03] GAILDRAT V., Modélisation déclarative d’environnements virtuels: création de scènes et de formes complexes par l’énoncé de propriétés et l’emploi d’interactions gestuelles, HDR Thesis, IRIT, France, 2003.

[GOL 89] GOLDBERG D.E., *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison Wesley, 1989.

[HAO 14] HAO J.K., SOLNON C., “Méta-heuristiques et intelligence artificielle”, Chapitre du livre *Algorithmes pour l’intelligence artificielle*, Editions Cepadues, 2014.

[ISH 96] ISHIBUCHI H., MURATA T., “Multi-objective genetic local search algorithm”, *Proceedings of 3rd IEEE International Conference on Evolutionary Computation*, pp. 119–124, 1996.

[ISH 02] ISHIBUCHI H., YOSHIDA, T., MURATA T., “Balance between genetic search and local search in hybrid evolutionary multi-criterion optimization algorithms”, *GECCO ‘02 Proceedings of the Genetic and Evolutionary Computation Conference*, pp. 1301–1308, 2002.

[JAS 02] JASZKIEWICZ A., “Genetic local search for multiple objective combinatorial optimization”, *European Journal of Operational Research,*, vol. 371, no. 1, pp. 50–71, 2002.

[KAT 13] KATANOSAKA T., SATO H., OYAMA S. *et al.*, “A preference search system using an interactive genetic algorithm”, *Proceedings of the International MultiConference of Engineers and Computer Scientists (IMECS)*, Hong Kong, vol. I, pp. 66–69, March 2013.

[KIC 06] KICINGER R., ARCISZEWSKI T., Empirical Analysis of Memetic Algorithms for Conceptual Design of Steel Structural Systems in Tall Buildings, George Mason University, Fairfax, 2006.

[KOZ 94] KOZA J.R., *Genetic Programming II: Automatic Discovery of Reusable Programs*, MIT Press, Cambridge, 1994.

[LAR 01] LARRANAGA P., LOZANO J.A., *Estimation of Distribution Algorithms: A New Tool for Evolutionary Computation*, Kluwer Academic Publishers, 2001.

[LEF 07] LEFORT-MATHIVET V., Evolution de second ordre et algorithmes évolutionnaires: l'algorithme RBF-Gene, PhD Thesis, University of Lyon, INSA Lyon, 2007.

[LER 07] LE RICHE R., SHOENAUER M., SEBAG M., "Un état des lieux de l'optimisation évolutionnaire et de ses implications en sciences pour l'ingénieur", in *Modélisation Numérique : défis et perspectives, Traité Mécanique et Ingénierie des Matériaux*, Hermes-Lavoisier, 2007.

[LI 09] LI H., ZHANG Q., "Multiobjective optimization problems with complicated pareto sets, MOEA/D and NSGA-II", *IEEE Transactions on Evolutionary Computation*, vol. 13, no. 2, pp. 284–302, 2009.

[LIU 13] LIU H.L., GU F., ZHANG Q., "Decomposition of a multiobjective optimization problem into a number of simple multiobjective subproblems", *IEEE Transactions on Evolutionary Computation*, vol. 18, no. 3, pp. 450–455, 2013.

[LLO 05] LLORA X., SASTRY K., GOLDBERG D.E. *et al.*, Combating User Fatigue in an IGA, Illinois Genetic Algorithms Laboratory, 2005.

[LUT 05] LUTTON E., "Darwinisme artificiel: une vue d'ensemble", *Traitement du signal*, vol. 22, no. 4, pp. 339–354, 2005.

[MAI 11] MAITRE O., GPGPU for evolutionary algorithms, PhD Thesis, University of Strasbourg, 2011.

[MAR 13a] MARSAULT X., "A multiobjective and interactive genetic algorithm to optimize the building form in early design stages", *Building Simulation 2013*, Chambéry, pp. 809–816, 2013.

[MCG 11] MC GINLEY B., MAHER J., O'RIORDAN C. *et al.*, "Maintaining healthy population diversity using adaptive crossover, mutation and selection (Acromuse)", *IEEE Transactions on Evolutionary Computation*, vol. 15, no. 5, pp. 692–714, 2011.

[NER 09] NERI F., TIRRONEN V., *Recent Advances in Differential Evolution: A Survey and Experimental Analysis*, Springer, 2009.

[NGO 14] NGO M., LABAYRADE R., "Multi-genomic algorithms", *IEEE Symposium on Computational Intelligence in Multi-Criteria Decision-Making (MCDM)*, pp. 48–57, 2014.

[PAI 11] PAILHES J., COLLIGNAN A., SEBASTIAN P. *et al.*, "Modélisation et optimisation en conception multi-objectifs", *20ème congrès français de mécanique*, Besançon, available at: http://hdl.handle.net/2042/46261, August 2011.

[QUI 08] QUIROZ J.C., SUSHIL J.L., BANERJEE J.L., "A model of creative design using collaborative interactive genetic algorithms", *Design Computing and Cognition DCC'08*, Springer, pp. 397–416, 2008.

[QUI 09] QUIROZ, J.C., SUSHIL, J.L., BANERJEE, J.L. *et al.*, Reducing user fatigue in interactive genetic algorithms by evaluation of population subsets, IEEE report, 2009.

[REC 72] RECHENBERG I., *Evolution strategie: Optimierung Technisher Systeme nach Prinzipien des Biologischen Evolution*, Fromman-Hozlboog Verlag, Stuttgart, 1972.

[SOL 10] SOLNON C., *Ant Colony Optimization and Constraint Programming*, ISTE, London and John Wiley & Sons, New York, 2010.

[VIL 12] VILLA C., Optimisation multicritère prenant en compte les préférences de panels de sujets. Application à l'éclairage de bureaux, Doctoral Thesis, Ecole Doctorale MEGA, Lyon, 2012.

[WOL 95] WOLPERT D.H., MACREADY W.G., No free lunch theorems for search, Technical Report SFI-TR-95-02-010, Santa Fe Institute, 1995.

[ZHA 07] ZHANG Q., LI H., "MOEA/D: a multiobjective evolutionary algorithm based on decomposition", *IEEE Transactions on Evolutionary Computation*, vol. 11, no. 6, pp. 712–731, 2007.

Architecture

[ABE 14] ABERGEL V., "Modes de représentation morphologique de modèles issus d'EcCoGen", stage d'initiation à la recherche, ENSA de Lyon, 2014.

[ALE 77] ALEXANDER C., ISHIKAWA S., SILVERSTEIN M., *A Pattern Language – Towns, Buildings, Construction*, Oxford University Press, 1977.

[ALE 02] ALEXANDER C., *The Nature of Order. I: The Phenomenon of Life*, The Center for Environmental Structure, 2002.

[ALE 04] ALEXANDER C., *The Nature of Order. II: The Process of Creating Life*, The Center for Environmental Structure, 2004.

[ALE 05] Alexander C., *The Nature of Order. III: A Vision of a Living World*, The Center for Environmental Structure, 2005.

[AND 13] ANDREOTTI A., Interview: Rachel Armstrong, Innovative Scientist Who Wants to Grow Architecture, available at; https://www.nextnature.net/2013/07/interview-rachel-armstrong/, 2013.

[BEM 36] BEMIS A.F., *The Evolving House: Rational Design*, vol. 3, MIT Press, Cambridge and Batsford, London, 1936.

[BES 08b] BESSERUD K., COTTEN J., "Architectural genomics", *ACADIA Conference*, Minneapolis, USA, pp. 238–245, 2008.

[BIN 14] BING X., YI C., "Comparative research on the methods of low carbon architecture implementation", *Zero-carbon Buildings Today and in the Future*, Birmingham, pp. 67–74, 2014.

[BOL 10] BOLLINGER K., GROHMANN M., TESSMANN O., "Structured becoming evolutionary processes in design engineering", *The New Structuralism: Design, Engineering and Architectural Technologies*, John Wiley & Sons, Ltd, p. 34, 2010.

[CHU 12] CHUPIN J.P., *Analogie et théorie en architecture – de la vie, de la ville et de la conception, même*, Infolio, 2012.

[COA 10] COATES, P., *Programming Architecture*, Routledge, 2010.

[COR 07] CORCUFF M.P., Penser l'espace et les formes, Doctoral Thesis, University of Rennes, 2007.

[DEB 06] DE BOTTON A., *L'architecture du bonheur*, Mercure de France, 2006.

[DIL 09] DILLENBURGER B., BRAACH M., HOVESTADT L., "Building design as individual compromise between qualities and costs: a general approach for automated building permanent cost and quality control", *CAAD Futures*, Montréal, Canada, pp. 458–471, 2009.

[FRA 95] FRAZER J., *An Evolutionary Architecture: Themes VII*, Architectural Association Publications, 1995.

[FRA 02] FRAZER J., "Generative and evolutionary techniques for building envelope design", *Generative Art*, Milan, Italy, 2002.

[HEN 08] HENSEL M., *Versatility and Vicissitude*, John Wiley & Sons, 2008.

[HEN 10] HENSEL M., "Performance-oriented architecture towards a biological paradigm for architectural design and the built environment", *FORMakademisk*, vol. 3, no. 1, pp. 36–56, 2010.

[KOL 00] KOLAREVIC B., "Digital morphogenesis and computational architectures", *Proceedings from Sigradi*, Rio de Janeiro, pp. 98–103, 2000.

[KOL 05] KOLAREVIC B., *Architecture in the Digital Age: Design and Manufacturing*, Taylor & Francis, 2005.

[KOL 10] KOLAREVIC B., KLINGER K., *Manufacturing Material Effects – Rethinking Design and Making in Architecture*, Routledge, Taylor & Francis, 2010.

[MAR 05] MARSAULT X., “Generation of textures and geometric pseudo-urban models with the aid of IFS, “Chaos in Art and Architecture””, *International Journal of Dynamical System Research*, vol. I, no. 3, pp. 1–18, 2005.

[MAR 06] MARCHAND B., “La nature organique des formes de la croissance. Le cas particulier des structures en nappes horizontales”, *Matières: Croissance*, vol. 8, pp. 21–34, 2006.

[MAR 16] MARSAULT X., LEQUAY H., “Eco-conception générative pré-architecturale: jusqu’où peut-on aller? Enjeux, possibilités, méthodes”, *SCAN16: Séminaire de Conception Architecturale Numérique*, Ecole Nationale Supérieure d’Architecture de Toulouse, pp. 195–207, September 2016.

[OKU 11] OKUDA S., PING C.L., “Form follows performance – structural optimization and the cost-effectiveness of digital fabrication”, *ECAADE*, pp. 269–278, 2011.

[OST 10] OSTERLUND T., Methods for morphogenesis and ecology in architecture, Diploma Work, Department of Architecture, University of Oulu, 2010.

[ROU 10] ROUDAVSKI S., “Towards morphogenesis in architecture”, *International Journal of Architecture Computing*, vol. 7, no. 3, pp. 345–374, 2010.

[SAF 61] SAFDIE M., A three-dimensional modular building system, Thesis, University of Montreal, Canada, 1961.

[SAL 09] SALINGAROS N., ALEXANDER C., HANSON B. *et al.*, *Anti-architecture et deconstruction*, Umbau-Verlag, 2009.

[SAS 07] SASAKI M., ITO, T., ISOZAKI, A., *Morphogenesis of Flux Structure*, Architectural Association Publications, 2007.

[SOD 04] SODDU C., “Argenia: artificial DNA and visionary variations”, *SIGraDi: Proceedings of the 8th Iberoamerican Congress of Digital Graphics*, Porte Alegre, Brazil, pp. 501–504, 2004.

[STO 13] STOJANOVIC D., “The promise of performative, relational, genetic and scripted models in architectural design”, *Architecture and Civil Engineering*, vol. 11, no. 1, pp. 47–59, 2013.

[TAY 08] TAYLOR A.K., *Design Engineering*, Actar, 2008.

Creativity and human–machine interfaces

[AND 08] ANDEL P.V., BOURCIER D., *De la sérendipité dans la science, la technique, l'art et le droit : leçons de l'inattendu*, L'Act Mem, 2008.

[BOT 12] BOTON C., HALIN G., KUBICKI S., "A metamodel to describe nD CAD visualization as Coordinated Multiple Views", *International Conference CDVE*, Osaka, Japan, 2012.

[DAR 94] DARSES F., FALZON P., "La conception collective: une approche de l'ergonomie cognitive", *Communication au séminaire du GDR CNRS FROG, "coopération et conception"*, Toulouse, December 1994.

[FAV 06] FAVRE J.-M., ESTUBLIER J., BLAY-FORNARINO M., *L'ingénierie dirigée par les modèles au-delà du MDA*, Hermes-Lavoisier, Paris, 2006.

[FLE 97] FLEMMING U.B., SURESH K., JOHN B.E., "Mismatched metaphor: user vs system model in computer-aided drafting", *Design Studies*, vol. 18, no. 4, pp. 349–368, 1997.

[GER 91] GERO J.S., MAHER M.L., "Mutation and analogy to support creativity in computer aided design", *Paper CAAD Futures Conference*, pp. 261–270, 1991.

[GER 93] GERO J.S., MAHER M.L. (eds), *Modeling Creativity and Knowledge-Based Creative Design*, Lawrence Erlbaum Associates, Hillsdale, 1993.

[GER 01] GERO J.S., SAUNDERS R., "Artificial creativity: a synthetic approach to the study of creative behaviour", in GERO J.S. (ed.), *Computational and Cognitive Models of Creative Design V*, University of Sydney, Australia, 2001.

[JAC 96] JACOB B.L., "Algorithmic composition as a model of creativity", *Organised Sound*, vol. 1, no. 3, pp. 157–165, 1996.

[KUB 07] KUBICKI S., HALIN G., GUERRIERO A., "Multi-visualization of the cooperative context in building construction activity A Model-B", *IV 2007 – 11th International Conference on Information Visualisation*, Zürich, Switzerland, pp. 590–595, 2–6 July 2007.

[LUC 05] LUCQUIAUD V., "Proposition d'un noyau et d'une structure pour les modèles de tâches orientés utilisateurs", *Proceedings of the 17th Conference on 17ème Conférence Francophone sur l'Interaction Homme-Machine*, pp. 83–90, 2005.

[MAL 01] MALCURAT O., Spécification d'un environnement logiciel d'assistance au travail coopératif dans le secteur de l'architecture et du BTP, PhD Thesis, Science for Architecture, National Polytechnic Institute of Lorraine, 2001.

[MAR 12a] MARIN P., MARSAULT X., SALERI R. *et al.*, "Creativity with the help of evolutionary design tool", *ECAADE: Digital Physicality | Physical Digitality*, Faculty of Architecture, Czech Technical University, Prague, Czech Republic, vol. 1, pp. 675–682, 2012.

[REA 07] REAS C., FRY B., *Processing: A Programming Handbook for Visual Designers and Artists*, MIT Press, 2007.

[SOT 05] SOTTET J.S., CALVARY G., FAVRE J.M., "Ingénierie de l'interaction homme-machine dirigée par les modèles", *IDM, Premières Journées sur l'Ingénierie Dirigée par les Modèles*, 2005.

[VAN 93] VANDERDONCKT J.M., BODART F., "Encapsulating knowledge for intelligent automatic interaction objects selection", *Proceedings of the INTERACT'93 and CHI'*, pp. 424–429, 1993.

[ZIG 11] ZIGNALE D., "A model-based method for the design of services in collaborative business environments", *Proceedings of IESS 1.1: Second International Conference on Exploring Services Sciences*, Geneva, Switzerland, pp. 68–82, 2011.

Eco-design, ecology, sustainable development

[ASS 15] ASSOCIATION HQE, Règles d'application pour l'évaluation environnementale des bâtiments neufs, Réalisées par le CSTB avec le soutien technique et financier de la DHUP, 2015.

[BBC 17] BBCA, Référentiel de labellisation des bâtiments neufs, v2.0, Association BBCA, February 2017.

[BEN 11] BENEFIS, Projet ANR 2011 VILD 001 01 – CSTB/DEE/EICV/15-001, 2011.

[BÈS 14] BES G., DURANO M., NORGAARD ROCKVAM A., *Nos limites – pour une écologie intégrale*, Editions Le Centurion, 2014.

[BLE 14] BLEIN J., Les matériaux de construction écologiques: quels critères prendre en compte pour les choisir?, Master's Dissertation, ENSAL, 2014.

[CAM 01] CAMPREDON J.P., MARTIN E., CROCI D., Habiter autrement: regards sur une architecture environnementale, *Les cahiers de Cantercel*, EDISUD, 2001.

[COU 10] COUTARD O., LEVY J.P., *Ecologies urbaines*, vol. 85/3, Géocarrefour, 2010.

[FER 14] FERRARA M., BENGISU M., "Intelligent design with chromogenic materials", *Journal of the International Colour Association*, vol. 13, pp. 54–66, 2014.

[GAD 09] GADREY J., *Adieu à la croissance*, Alternatives Economiques, 2009.

[GAL 13] GALLAS M.A., HALIN G., "DaylightGen: from daylight intentions to architectural solutions. Implementation and experimentation of a generative and parametric design tool", *Proceedings of the 31st eCAADe Conference. eCAADe: Conferences 2*, Delft University of Technology, The Netherlands, vol. 2, pp. 107–116, 2013.

[GEN 13] GENUYS L., Evaluation Environnementale des Bâtiments – Vers une reproductibilité des résultats, Thesis Ecole Centrale de Lyon, 2013.

[GHO 11] GHOLIPOUR V., Ecoconception collaborative de bâtiments durables, Thesis, National Polytechnic Institute of Lorraine, 2011.

[GOB 11] GOBIN C., "Écoconception marqueur d'un ré-engineering de la construction", *Techniques de l'ingénieur L'ingénierie de la construction*, base documentaire : TIB236DUO (ref. article : c3020), 2011.

[GUT 14] GUTAI M., Liquid engineering – towards new sustainable model for architecture and city, JSPS Postdoctoral Research, Department of Architecture, University of Tokyo, 2014.

[LAM 14] LAME G., Outils d'écoconception pour le bâtiment, Master's Thesis, Industrial Engineering Laboratory of the Ecole Centrale de Paris, 2014.

[LAM 15] LAME G., LEROY Y., "Ecoconception des bâtiments: pratiques actuelles et freins à l'utilisation des outils d'écoconception - Une étude en France", *14e colloque AIP PRIMECA*, Aime La Plagne, France, March 2015.

[LLA 14] LLACH D.C., ARGUN A., DIMITROV D. *et al.*, "Acacia : a simulation platform for highly responsive Smart facades", *SimAUD : Symposium on Simulation for Architecture and Urban Design*, Tampa, FL, Article no. 6, 2014.

[MAR 12b] MARIN P., MARSAULT X., SALERI R. *et al.*, "L'Eco-Conception Générative: Une illustration de la pensée complexe", *SCAN12 : Séminaire de Conception Architecturale Numérique, Complexité(s) des Modèles de l'Architecture Numérique*, Ecole Nationale Supérieure d'Architecture de Paris La Villette, France, pp. 213–223, 2012.

[MIN 13] MINISTERE DE L'ECOLOGIE, DU DEVELOPPEMENT DURABLE ET DE L'ENERGIE, Repères – Chiffres clés du climat – France et Monde, Service de l'observation et des statistiques, 2013.

[PER 12] PERINO M., "Responsive building elements – actual developments and trends with IEA", *ANNEX 44, Integrating Environmentally Responsive Building Elements*, 2012.

[PEU 13a] PEUPORTIER B., *Écoconception des ensembles bâtis et des infrastructures*, Presse des Mines, 2013.

[PEU 13b] PEUPORTIER B., THIERS S., GUIAVARCH A., *Eco-Design of Buildings Using Thermal Simulation and Life Cycle Assessment*, Centre for Energy and Processes, MINES ParisTech, Paris, 2013.

[RÉF 16] REFERENTIEL ENERGIE CARBONE POUR LES BATIMENTS NEUFS, Ministère de l'Environnement de l'Energie et de la Mer, Ministère du Logement et de l'Habitat Durable, 2016.

[SCH 09] SCHLUETER A., THESSELING F., "Building information model based energy/exergy performance assessment in early design stages", *Automation in Construction*, vol. 18, no. 2, pp. 153–163, 2009.

[SER 01] SERRES M., *Hominescence*, Editions le Pommier, 2001.

[TIS 13] TISSOT-COLLE C., JOUZEL J., La transition énergétique 2020–2050: un avenir à bâtir, une voie à tracer, Conseil Economique Social et Environnemental, 2013.

[YEP 11] YEPEZ-SALMON G., Construction d'un outil d'évaluation environnemental des éco-quartiers: vers une méthode systémique de mise en œuvre de la ville durable, PhD Thesis, University of Bordeaux 1, 2011.

Energy, buildings and cities

[ADE 11] ADEME – Etat de l'art des indicateurs et des outils de calcul de consommation énergétique et de gaz à effet de serre – De l'échelle du quartier à celle de l'agglomération, Synthèse des travaux et identification de pistes de recherche à approfondir, Report from ADEME, 48 pages, 2011.

[ALH 01] AL-HOMOUD M.S., "Computer-aided building energy analysis techniques", *Building and Environment*, vol. 36, pp. 421–433, 2001.

[AND 06] ANDERSON P., Climate Change Futures: Health, Ecological And Economic Dimensions, The Center for Health and the Global Environment, Harvard Medical School, Boston, MA, 2006.

[ARM 15] ARMAND-DECKER S., Développement d'une méthode d'optimisation multiobjectif pour la construction bois: prise en compte du confort des usagers, de l'impact environnemental et de la sécurité de l'ouvrage, PhD Thesis, University of Bordeaux, 2015.

[ASH 09] ASHRAE, "Climate Design Information", available at: ashrae.org, 2009.

[ATT 12] ATTIA S., GRATIA E., DE HERDE A. *et al.*, "Simulation-based decision support tool for early stages of zero-energy building design", *Energy and Buildings*, vol. 49, pp. 2–15, 2012.

[BAR 05] BARNABY C.S., SPITLER J.D., "Development of the residential load factor method for heating and cooling load calculations", *ASHRAE Transactions*, vol. 111, no. 1, pp. 291–307, 2005.

[BEN 03] BENISTON M., "The 2003 heat wave in Europe: a shape of things to come? An analysis based on Swiss climatological data and model simulations", *Geophysical Research Letters*, vol. 31, no. L02202, p. 1, 2003.

[BER 04] BERLING-WOLFF S., WU J., "Modeling urban landscape dynamics: a review", *Ecological Research*, vol. 19, no. 1, pp. 119–129, 2004.

[BON 15] BONTEMPS S., Validation expérimentale de modèles: application aux bâtiments basse consommation, Thesis, University of Bordeaux, 2015.

[CAR 04] CARDONNEL C., Bilan thermique en résidentiel: pourquoi faire compliqué quand on peut faire simple? *CFP*, no. 667 (chaud - froid - plomberie), April 2004.

[CAT 08a] CATALINA T., VIRGONE J., BLANCO E., "Development and validation of regression models to predict monthly heating demand for residential buildings", *Energy and Buildings*, vol. 40, pp. 1825–1843, 2008.

[CAT 08b] CATALINA T., VIRGONE J., ROUX J.J. *et al*., "Effet de l'inertie thermique, de la surface vitrée et du coefficient de forme sur les besoins en chauffage d'une habitation", *IBPSA*, hal-00411796, 2008.

[CAT 11] CATALINA T., VIRGONE J., IORDACHE V., "Study on the impact of the building form on the energy consumption, building simulation", *International Building Performance Simulation Association Conference*, Sydney, Australia, pp. 1726–1729, 2011.

[CAT 13] CATALINA T., IORDACHE V., CARACALEANU B., "Multiple regression model for fast prediction of the heating energy demand", *Energy and Buildings*, vol. 57, pp. 302–312, 2013.

[CLA 01] CLARKE J.A., *Energy Simulation in Building Design*, 2nd ed., Butterworth-Heinemann, Oxford, 2001.

[DAL 12] DALL'O' G., SARTO L., SANNA N. *et al.*, "Comparison between predicted and actual energy performance for summer cooling in high-performance residential buildings in the Lombardy region (Italy)", *Energy and Buildings*, vol. 54, pp. 234–242, 2012.

[DRI 92] DRISCOLL D.M., "Thermal comfort indexes: current uses and abuses", *National Weather Digest*, vol. 17, pp. 33–38, 1992.

[EIK 14] EIKEMEIER S., WIMMER R., "Life cycle habitation – zero carbon building concepts", *Zero-Carbon Buildings Today and in the Future*, Birmingham, pp. 33–39, 2014.

[END 06] ENDLICHER W., JENDRITZKY G., FISCHER J. *et al.*, "Heat waves, urban climate and human health", in WANG W., KRAFFT T., KRAAS F. (eds), *Global Change, Urbanization and Health*, Meteorological Press, Beijing, 2006.

[GAR 11] GARNIER A., *Le bâtiment à énergie positive*, Eyrolles, 2011.

[GOS 13] GOSSARD D., LARTIGUE B., THELLIER F., "Multi-objective optimization of a building envelope for thermal performance using genetic algorithms and artificial neural network", *Energy and Buildings*, vol. 67, pp. 253–260, 2013.

[GRA 13] GRANADEIRO V., DUARTE J.P., CORREIA J.R. *et al.*, "Building envelope shape design in early stages of the design process: integrating architectural design systems and energy simulation", *Automation in Construction*, vol. 32, pp. 196–209, 2013.

[GÜN 16] GÜNERALP B., ZHOU Y., ÜRGE-VORSATZ D. *et al.*, "Global scenarios of urban density and its impacts on building energy use through 2050", *Proceedings of the National Academy of Science*, November 2016. doi: 10.1073/pnas.1606035114.

[HOU 53] HOUSING AND HOME FINANCE AGENCY, Basic Principles of Modular Coordination, Lecture notes, US Division of Housing Research, Washington, D.C., 1953.

[HUA 06] HUANG M.J., EAMES P.C., HEWITT N.J., "The application of a validated numerical model to predict the energy conservation potential of using phase change materials in the fabric of a building", *Solar Energy Materials and Solar Cells*, vol. 90, no. 13, pp. 1951–1960, 2006.

[HUI 01] HUIZENGA C., ZHANG H., ARENS E., "A model of human physiology and comfort for assessing complex thermal environments", *Buildings and Environment*, vol. 36, p. 691, 2001.

[HUW 14] HUWS H., JANKOVIC L., "Birmingham zero carbon house: making it stay zero carbon through climate change", *Zero-Carbon buildings Today and in the Future*, Birmingham, pp. 11–12, 2014.

[JON 13] JONES P., LANNON S., LI X. *et al.*, Intensive Building Energy Simulation at Early Design Stage, Welsh School of Architecture, Cardiff University, 2013.

[KAL 06] KALOGIROU S.A., "Artificial neural networks in energy applications in buildings", *International Journal of Low-Carbon Technologies*, vol. 1, no. 3, pp. 201–216, 2006.

[LAG 13] LAGADEC R., Morphologie des bâtiments et performances énergétiques: évaluation d'une méthode générative pour l'optimisation en phase amont, Master's Thesis, ENSA de Lyon, 2013.

[LIN 13] LIN B., YU Q., LI Z. *et al.*, "Research on parametric design method for energy efficiency of green building in architectural scheme phase", *Frontiers of Architectural Research*, vol. 2, pp. 11–22, 2013.

[LOZ 11] LOZINGUEZ E., Méthodes de Monte Carlo pour l'optimisation multicritère d'un bâtiment prenant en compte le ressenti subjectif et incertain des occupants, Master MEGA, Laboratoire LASH, ENTPE, 2011.

[MAN 03] MANSOURI Y., ALLARD F., MUSY M., "Conceptual implementation of natural ventilation strategy", *Eighth International IBPSA Conference*, Eindhoven, Netherlands, pp. 815–822, 11–14 August 2003.

[MAR 10] MARIN P., Exploration des mécanismes évolutionnaires appliqués à la conception architecturale, PhD Thesis, Université de Nancy, 2010.

[MAR 13b] MARIN P., MARSAULT X., MAVROMATIDIS L.E. *et al.*, "Ec-Co-Gen: an evolutionary simulation assisted design tool for energy rating of buildings in early design stage to optimize the building form", *Building Simulation 2013*, Chambéry, pp. 2201–2208, 2013.

[MAV 11] MAVROMATIDIS L.E., Phénomènes de transfert thermique dans les PMR, Doctoral Thesis, ENTPE-INSA, Lyon, 2011.

[MAV 13a] MAVROMATIDIS L.E., BYKALYUK A., LEQUAY H., "Development of polynomial regression models for composite dynamic envelopes' thermal performance forecasting", *Applied Energy*, vol. 104, pp. 379, 2013.

[MAV 13b] MAVROMATIDIS L.E., LEQUAY H., "Heterogeneous parameter investigation of dynamic building envelope's thermal insulating performance", *CLIMA, 11th REHVA World Congress & 8th International Conference on IAQVEC: Energy Efficient, Smart and Healthy Buildings*, Prague, Czech Republic, 2013.

[MAV 14b] MAVROMATIDIS L.E., MARSAULT X., LEQUAY H., "Daylight factor estimation at an early design stage to reduce buildings' energy consumption due to artificial lighting: a numerical approach based on Doehlert and Box-Behnken designs", *Energy*, vol. 65, pp. 488–502, 2014.

[MEE 04] MEEHL G.A., TEBALDI C., "More intense, more frequent, and longer lasting heat waves in the 21st Century", *Science*, vol. 305, p. 994, 2004.

[MEN 14] MENET J.L., GRUSCU I.C., *L'écoconception dans le bâtiment*, Dunod, 2014.

[MIR 13] MIRANDA FUENTES J., JOHANNES K., KUZNIK F. *et al.*, "Melting with convection and radiation in a participating phase change material", *Applied Energy*, vol. 109, pp. 454–461, 2013.

[NAU 16] NAULT E., Solar potential in early neighborhood design: a decision-support workflow based on predictive models, Thesis, Ecole Polytechnique Fédérale de Lausanne, 2016.

[NOW 10] NOWACKY C., SALAT S., "De l'importance de la morphologie dans l'efficience énergétique des villes", *Liaison Energie-Francophone*, vol. 86, pp. 141–146, 2010.

[OLO 01] OLOFSSON T., ANDERSSON S., "Long-term energy demand predictions based on short term measured data", *Energy and Buildings*, vol. 33, no. 2, pp. 85–91, 2001.

[PAS 08] PASUPATHY A., VELRAJ R., SEENIRAJ R.V., "Phase change material-based building architecture for thermal management in residential and commercial establishments", *Renewable and Sustainable Energy Reviews*, vol. 12, no. 1, pp. 39–64, 2008.

[PAT 05] PATZ J., CAMPBELL-LENDRUM D., HOLLOWAY T. *et al.*, "Impact of regional climate change on human health", *Nature*, vol. 438, p. 310, 2005.

[RÉG 12] REGLEMENTATION THERMIQUE, "Annexes techniques, méthode de calcul Th-BCE développée par le CSTB", available at: www.cstb.fr, 2012.

[RIV 13] RIVALLAIN M., Etude de l'aide à la décision par optimisation multicritère des programmes de réhabilitation énergétique séquentielle des bâtiments existants, PhD Thesis, University Paris-Est, 2013.

[SAL 07] SALINGAROS N., *The Future of Cities*, Nikos A. Salingaros & Umbau-Verlag, Solingen, Germany, 2007.

[SCH 04] SCHÄR C., VIDALE P.L., LÜTHI D. *et al.*, "The rôle of increasing temperature variability in European summer heatwaves", *Nature*, vol. 427, p. 332, 2004.

[SCH 16] SCHWARTZ Y., RASLAN R., MUMOVIC D., "Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimization: a building refurbishment case study", *Energy*, vol. 97, pp. 58–68, 2016.

[SHE 12] SHEN X., ZHANG G., BJERG B., "Investigation of response surface methodology for modelling ventilation rate of a naturally ventilated building", *Building and Environment*, vol. 54, pp. 174–185, 2012.

[TZI 11] TZIVANIDIS C., ANTONOPOULOS K.A., GIOTI F., "Numerical simulation of cooling energy consumption in connection with thermostat operation mode and comfort requirements for the Athens buildings", *Applied Energy*, vol. 88, no. 8, pp. 2871–2884, 2011.

[VEL 15] VELAZQUEZ ROMO E., Processus de conception énergétique de bâtiments durables, Thesis, University of Bordeaux, 2015.

[WAN 06] WANG S., XU X., "Simplified building model for transient thermal performance estimation using GA-based parameter identification", *International Journal of Thermal Sciences*, vol. 45, no. 4, pp. 419–432, 2006.

[YIK 01] YIK F.W.H., BURNETT J., PRESCOTT I., "Predicting air-conditioning energy consumption of a group of buildings using different heat rejection methods", *Energy and Buildings*, vol. 33, no. 2, pp. 151–166, 2001.

[YOK 09] YOKOYAMA R., WAKUI T., SATAKE R., "Prediction of energy demands using neural network with model identification by global optimization", *Energy Conversion and Management*, vol. 50, no. 2, pp. 319–27, 2009.

Morphogenesis, biology, nature, biomimetry

[BAD 12] BADARNAH L., Towards the LIVING Envelope: Biomimetics for Building Envelope Adaptation, Delft University of Technology, Netherlands, 2012.

[BAD 15] BADARNAH L., "A methodology for the generation of biomimetic design concepts", *Architectural Science Review*, vol. 58, pp. 120–133, 2015.

[BAL 96] BALDWIN J.M., Un nouveau facteur en évolution, 1896.

[BAQ 03] BAQUIAST J.P., JACQUEMIN C., "L'auto-organisation de la parole", available at: http://www.automatesintelligents.com/labo/2003/dec/pyo.html, 2003.

[BAQ 04] BAQUIAST J.P., JACQUEMIN C., "La morphogénèse", available at: http://www.automatesintelligents.com/echanges/2004/jan/morphogenese.html, 2004.

[BEN 97] BENYUS J., *Biomimicry – Innovation Inspired by Nature*, Harper-Collins, 1997.

[BOU 06] BOURGINE P., LESNE A., *Morphogénèse, l'origine des formes*, Belin, Paris, 2006.

[BUE 09] BUELOW P.V., EMBDEN A., TURRIN M., "Structural DNA: genetic exploration of biological micro structures for architectural applications", *ACSA Southwest*, Albuquerque, New Mexico, pp. 110–124, 2009.

[CAL 08] CALLEBAUT V., *ARCHIBIOTIC*, Editeur Bruce Q. Lan, 2008.

[CHA 06] CHALINE J., *Quoi de neuf depuis Darwin*, Ellipses, Paris, 2006.

[COL 10] COLLINS F., *The Language of Life: DNA and the Revolution in Personalized Medicine*, Harper-Collins, 2010.

[CON 09] CONWAY-MORRIS S., "The predictability of evolution: glimpses into a post-Darwinian world", *Naturwissenschaften*, vol. 96, no. 11, pp. 1313–1337, 2009.

[CRU 16] CRUZ E., "Biomimicry World Tour: research project in architecture and civil engineering 2015–2016", available at: www.biomimicry-worldtour.com, 2016.

[DED 05] DE DUVE C., *Singularités: Jalons sur les chemins de la vie*, Odile Jacob, Paris, 2005.

[DEN 02] DENTON M.J., MARSHALL C.J., LEGGE M., "Protein folds as platonic forms", *Journal of Theoretical Biology*, vol. 219, no. 3, pp. 325–342, 2002.

[FRO 64] FROMM E., *The Heart of Man*, Harper & Row, 1964.

[LAM 09] LAMARCK J.B., *Philosophie Zoologique*, G.F. Flammarion, 1809.

[OUD 13] OUDEYER P.Y., *Aux sources de la parole: auto-organisation et évolution*, Odile Jacob, Paris, 2013.

[PAL 09] PALDI A., *L'hérédité sans gène*, Editions Le Pommier, 2009.

[PAW 11] PAWLYN M., *Biomimicry in Architecture*, vol. 15, Riba Publishing, 2011.

[PED 12] PEDERSEN ZARI M., "Ecosystem services analysis for the design of regenerative built environments", *Building Research & Information*, vol. 40, no. 1, pp. 54–64, 2012.

[STA 09] STAUNE J., *Au-delà de Darwin – pour une autre vision de la vie*, Editions Jacqueline Chambon, 2009.

[STI 06] STINY G., *Shape: Talking About Seeing and Doing*, MIT Press, 2006.

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