Adaptive Timber Towers. An Evolutionary Prototype for the 21st Century Skyscraper

Alessandro Buffi and Gian Maria Angelini

Abstract The biological metaphor introduced by computational design, as well as the increasing theoretical framework of parametric architecture, opens new perspectives for both wood and skyscraper design. At the intersection of architecture, biology, and computer science, avant-garde designers are reshaping the historical relationship between nature and architecture fostering a natural approach to design which results in: structural lightness, rational use of energy and elegance. Wood seems to be a perfect material to engage with this new period of design research, and while timber towers are getting higher, there is a strong interest in understanding to which extent wood can represent a valuable alternative to those materials that have characterized the recent architectural debate. Analyzing the emerging type of the wooden skyscraper within the context of globalization, technological advances, and ecology; the authors present their vision for the 21th-century skyscraper. Based on parametric design and evolutionary principles, the proposed model can adapt to different contexts and conditions, providing different solutions as the result of the interaction with the surrounding environment.

Keywords Parametric design · Form-finding · Environmental design
High-rise buildings · Complex timber structures · Evolutionary algorithms
Wooden skyscraper

1 Introduction

The biological metaphor introduced by computational design, as well as the increasing theoretical framework of Parametric Architecture (Schumacher 2011), open new perspectives for both wood and skyscraper design. At the intersection of Architecture,

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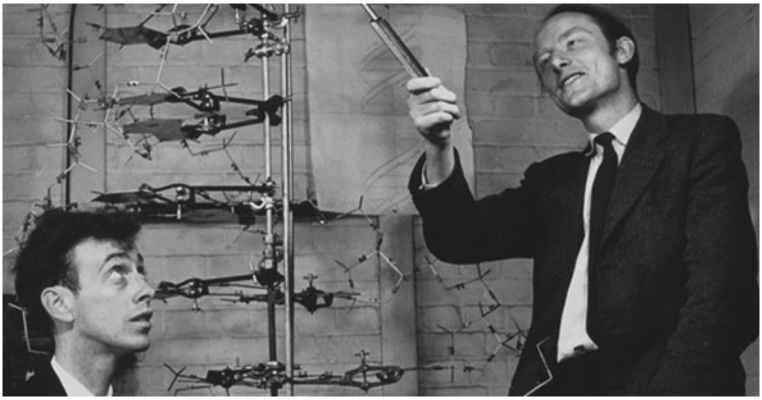

Fig. 1 James Watson and Francis Crick posing next to their DNA double helix model (1953)

Biology, and Computer Science, avant-garde designers are reshaping the historical relationship between Nature and Architecture fostering a natural approach to design which results in: structural lightness, rational use of energy and elegance. The background of such a natural approach to design comes from the nineteenth century's form-finders such as Robert Maillart, Pier Luigi Nervi, Sergio Musmeci, Eduardo Torroja, Riccardo Morandi, Felix Candela, Heinz Isle, Eladio Dieste, Buckminster Fuller, and Frei Otto (Pone 2011). We owe them the birth of the so-called hands-off approach to design, an approach in which decisions are not taken directly by the architect, yet following a cognitive process supported by both analytic and digital models (Bianconi et al. 2017).

Generative design systems give new impetus to this field of research allowing the designer to emulate natural processes or even invent new ones to create architectural organism characterized by the same efficiency and beauty of natural systems. In particular, the efficiency of living systems is the result of a slow evolutionary process, as explained by Darwin's theory of evolution and the possibility to apply this process to Architecture through Genetic Algorithms puts in the hands of the designer a powerful tool (Bianconi et al. 2017). Starting from the 1990s shift has been noticed in the way avant-garde architects have used new technologies of evolutionary biology, to address or depict the increased complexity that is noticed in today's architecture (Fasoulaki 2007). This shift has been fostered on the one hand by the advances in the field of genetic (Fig. 1) and computer science, with the development of bio-inspired algorithms, on the other by the experimentation of CAD technology (Fig. 2) in different design fields, with the development of innovative representation techniques.

With the windward of digital representation, the algorithm becomes a tool to configure, rather than a statical morphology, a generative model characterized by diversity and thus by adaptive behavior. Through the use of digital design tools, the designer can effectively handle heterogeneous information and complex associative rules; this opens to a series of optimization and form-finding strategies used to explore

Fig. 2 Ivan Sutherland working at the computer TX-2, MIT Lincoln Labs (1963). The Sketchpad Interface

the generative potential of the model and find optimal solutions. Furthermore, while generative systems allow to visualize and evaluate thousands of design options, a new assembly line allows creating thousand of variations of the same product, thus developing a direct link between what can be designed, and what can be built.

Within the emerging context of Industry 4.0 (Paoletti 2018), while robotics and smart manufacturing are reshaping the relationship between architecture and industrial production, the design, and construction process of the skyscraper has to be rethought. This building type historically based on mass production and economy of scale, is gradually moving to a new paradigm of industrial production based on custom and nonstandard elements characterized by a high-level of complexity. Even though the building industry has been slow in adopting this new paradigm (Benros and Duarte 2009), by applying techniques borrowed by automotive, naval and aerospace industry (Portoghesi 2007) the architect can go beyond the limitations imposed by mass-production moving to a design-driven manufacture that provides the designer with a high degree of freedom.

Timber structures become a central theme within this innovative trend and, in the light of the latest developments, wood has the potential to become the most advanced building material of 21st century. Thanks to its workability and its strength-to-weight ratio, it becomes an excellent material for structural expression and formal experimentation. Furthermore, its carbon-storing properties associated with the benefits on human health and comfort, make it more than an alternative to traditional construction materials. For this reason, different projects around the world have been built, triggered by the advances of engineered wood, and while timber structures are getting higher, there is a strong interest in understanding to which extend wood can represent a valuable alternative to those materials that have characterized the recent architectural debate.

2 The Skyscraper as an Adaptive Organism

> Adaptive capacity or adaptation has become a key ambition of the contemporary avant-garde trend that might suggest a comparison with natural organic systems. (Schumacher 2007)

In the design of a skyscraper, "productive machine" of enormous complexity (Willis 2004), the subjectivity of the individual contribution is subordinated to the objectivity of the result. This involves every aspect of the construction, affecting its aesthetic appearance "no longer product of an a priori creative idea, but result of a long process of elaboration and selection aimed to identify the best solution" (Biraghi 2008). In this sense, within this typology, form-finding strategies reach their maximum expression, supporting the designer in a complex exercise of problem-solving. In this process, "potential performance improvement can be explored using parametric multi-objective optimization aided by sophisticated evaluation tools, such as computational fluid dynamics and energy analysis software, to visualize and explore skyscraper generative potential (Imam and Kolarevic 2016)."

Within the context of globalization, the skyscraper is populating our planet as a ubiquitous universal building type, engaging with widely different contexts and climate conditions (Fig. 3). The only ways to make this process sustainable is through an effective adaptation to the site-specific climate conditions; namely by the use of traditional and vernacular architecture elements or by a conscious bio-climatic design approach based on both active and passive means (Yeang 1999). Skyscraper energy efficiency can be promoted by considering a climatically responsive design, where the orientation, the thermal properties of the building envelope and the effect of altitude become the main design tools (Saroglou et al. 2017). Strategies including building configuration and orientation, the location of the service core, the design of the building envelope to incorporate sun shading, integrated plantings, and the use of natural ventilation (Howeler 2005).

Ecological skyscrapers belong to an emerging area of design research characterized by innovative interdisciplinary explorations achieved through the total

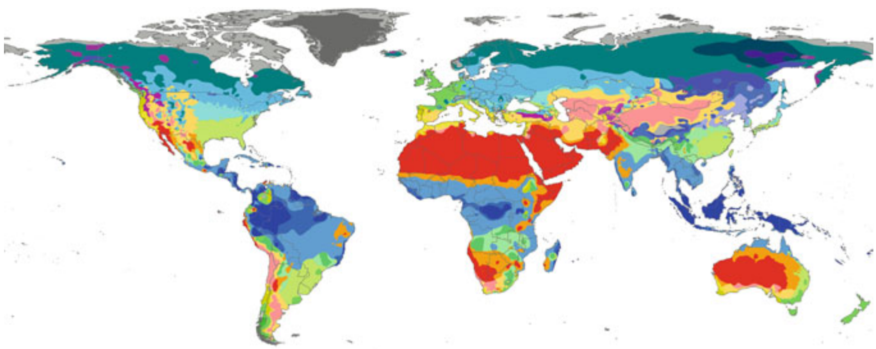

Fig. 3 The Global context: a variegated realm characterized by site-specific environmental forces. World map of Koppen-Geiger climate map (Murray C. Peel)

Fig. 4 Hōryū-ji in Japan, is one of the oldest wooden buildings in the world

integration of architecture, and engineering (Jahn and Sobek 1999) by blurring the boundaries of disciplines like biology and computer science. In particular, ecology, as a branch of biology, suggests the study of the relationship between organisms and their environment, a concept that suits surprisingly well also the discipline of architecture (Hensel and Menges 2006). Like a natural organism, the skyscraper is composed of a series of deeply integrated systems, each of which, interacting with its environment, contributes to defining the performances and the outcome of the building. Instead of assembling rigid and hermetic geometric figures, "each of this element should be parametrically malleable and participate in a dynamical play of mutual responsiveness as well as contextual adaptation (Schumacher 2010)."

By looking at the skyscraper as an adaptive organism, bio-inspired form-finding strategies can guide toward high performances, supporting the designer in a complex problem-solving process that takes into account heterogeneous data such as geometry, dynamic system of forces, and environmental conditions. Just like in Nature, where every living organism, through a slow evolutionary process, is subject to the logic of adaptation; in parametric design, tools like Genetic Algorithms (GA) can identify, through a fitness-based process, the optimal solution from a bioclimatic, structural and functional point of view (Causarano 2014). Since, in the late 60s, Ingo Rechenberg and his colleagues applied for the first time Genetic Algorithms to aerodynamic wing design (Rechenberg 1973) several designers mainly in the field of engineering started to use these fitness-based algorithms to solve complex design problems. Used as virtual prototyping tools in the field of mechanical and aerospace engineering genetic algorithms belong to the metaheuristic class of Evolutionary Algorithms and "are commonly used to generate high-quality solutions to optimization and search problems by relying on bio-inspired operators such as mutation, crossover, and selection (Mitchell 1996)."

3 The Era of Timber Towers

For more than a century, the skyscraper constructed with concrete and steel has had a leading role within the metropolis skyline. Those materials, given their exceptional structural properties, have represented the constructive solution for the designer of the modern era, and thank to their seismic resilience and high load-bearing capacity skyscrapers have achieved extraordinary heights. Unfortunately, steel and concrete industries appear to be among the highest carbon footprint industries in the world. It is assessed that altogether they are responsible for the 8% of global CO_2 emission. Therefore, it is worth asking whether there are alternative materials to steel and concrete which can guarantee the same static behavior while reducing its environmental impact.

The background for the global diffusion of timber towers can be found in ancient architecture; indeed wood has been one of the oldest construction material in the history of architecture, and Tall Wood buildings have existed for centuries. For instance, tall pagodas in Japan were built up to 19 stories in wood 1400 years ago and a few still stand today in high seismic and wet climate environments (Green 2012).

The Barsana Monastery (Fig. 5), standing at 56 m tall, is considered the tallest wooden structure in Europe. Whereas, Asia, within his historical tradition, offers a wide series of examples. The typical pagoda structure besides being an excellent example of the durability of wooden constructions, is also a type of structure that develops upwards with aesthetical purpose. The five-story pagoda of Hōryū-ji (Fig. 4) in Japan, standing at 32.45 m in height, is one of the oldest wooden building of the word. Originally built in the 7th century, the center pillar of the pagoda is estimated to have been felled in 594 ("Web Japan" 2007). Most recently, after the burns of the 19-story height Jiulong Temple in Mianzhu in December 2017, the Tianning Pagoda in Changzhou (Fig. 6) is the tallest pagoda in the world, with 13 stories and a height of 153.79 m (China Daily 2007).

In recent years, once studies and research proved the efficiency of Cross Laminated Timber (CLT) (Ceccotti et al. 2006), its usage for multi-story buildings sprout across the globe with extraordinary results, from Norway to Japan. In 2009, the first residential building constructed entirely in timber was completed in London. The

Fig. 5 The Barsana Monastery is considered the tallest wooden structure in Europe

Stadthaus, 24 Murray Grove is a nine-story high-rise designed by Waugh Thistleton Architects which could be considered as a pioneering project for its unique cross-laminated structural system. Made with prefabricated panels including cut-outs for windows and doors, this building was assembled within nine weeks, revealing the benefits regarding time-saving related to wooden structures (Thompson et al. 2009). In the meantime, following the first results, several CLT structural system have been developed around the world. The Brock Commons Tallwood House, completed in 2017, at the University of British Columbia in Vancouver stands 53 m high and is the tallest timber building constructed to date. Designed by the Canadian practice Acton Ostry Architects Inc., the 18-story skyscraper is composed by a concrete podium and lift cores, while glulam timber columns hold up cross-laminated timber floors and walls (Naturally Wood 2017).

In Europe, Norway is assuming a leading role, indeed it hosts Treet the tallest European wooden residential building, while the Mjøsa Tower that will be in 2019 the tallest wooden building in the world is under construction. Treet has been completed in 2015, this 14-story residential building located in the city of Bergen, is composed by load-carrying glulam trusses and two intermediate strengthened levels. A system of prefabricated building modules are stacked on top of the concrete basement and on

Fig. 6 Tianning Pagoda in Changzhou, China is currently the tallest pagoda in the world

top of the strengthened levels, while glass and metal sheeting on the facades protect the structural timber from weathering (Abrahamsen and Malo 2014).

Looking to the next future of timber technology, several exemplary projects can inspire the design of next-generation timber towers. Arup developed a project called Haut to create a 21-story tower in Amsterdam in 2020. Meanwhile, C.F. Moller and Anders Berensson Architects plans for respectively a 34-story and a 40-story skyscraper, both in Stockholm; and PLP Architecture and Cambridge University's proposed for an 80-story, 300-m high wooden building integrated within London's Barbican Centre. Furthermore, giving the results already obtained in different projects and the advancement of timber technology, this positive trend doesn't look to stop.

To date, the most ambitious timber tower project is represented by the W350 Sumitomo, in Tokyo. Called to be the tallest timber structure in the world, with its 350 m and 70 story it is estimated to cost 600 billion of yen and to be completed in 2041. The planned structure is a hybrid wood and steel structure made from 90% of wooden materials. In this visionary project, the interior structure of a pure wood will produce a calm space that exudes the warmth and gentleness of wood, creating like a forest, a habitat for living things (Sumitomo Forestry 2018). With the aim of "Change Cities in Forests," these ambitious project reflects the clear direction that the Japanese building industry is going to undertake in the near future. Indeed, Japan in order to promote forest regeneration, since 2010 is encouraging the shift to wooden structures for public buildings through the "Act for Promotion of Use of Wood in Public Buildings".

Meant to be reversible structures that can be almost fully recycled at the end of their life cycle, wooden skyscrapers become a vehicle to enable the sustainability of our planet. With the global population growth and increasing rates of urbanization, the demand for new high-rise buildings is constantly rising. If these new buildings are made of wood, they will not only act as a long-term carbon reservoir, but they will generate fewer emissions during their entire life cycle, representing meanwhile a healthy place to live or a stimulating workspace environment. The benefits related to wooden environments are multiple and strictly connected to the psychological and physiological well being. For instance, the feeling of natural warmth and comfort related to wood have the effect of lowering blood pressure and, heart rates reducing stress in favor of productivity and positive social interaction. Furthermore, wood performs as a moisture regulator, and sensible improves air quality within an interior space (Bergs 2002). In this sense wood is a perfect material to design an architectural organism whose adapt to both the environment and its inhabitants.

4 Evoluzione: Vision and Design Approach

Evoluzione (Fig. 7) is a design proposal presented by the authors at the SKYHIVE Skyscraper Challenge 2018 and awarded the BB Green Award. The concept of the project is to "propose, rather than a form, an architectural model characterized by variety and thus by adaptive behavior; an iconic prototype for a sustainable human evolution. The context of the project is planet earth, a variegated realm characterized by a range of site-specific environmental forces capable of informing the design process. Following the rules of nature, a form-finding strategy based on parametric design and evolutionary principles minimizes the use of matter and energy consumption through the specific climate data interpretation. In this context, natural lighting, strictly related to the office workers well-being, becomes one of the major driving forces. The result is a skyscraper capable of meeting the requirements of flexibility, comfort, and sustainability related to a working environment in continuous evolution."

Fig. 7 Evoluzione: adaptive wooden skyscraper in Santiago de Chile, Miami, Dubai and Hong Kong

4.1 Materials and Methods

As a method that can be used by designers in the early stage of design, the form-finding process developed in this research emerges from a bottom-up process that combines analysis, and experimentation in generative systems. Trying to put the geometry in relation with his environment the researchers create, through the definition of an algorithm, an integrated design process that encompasses three steps:

- Generative Model: definition of a generative model able to create a variety of feasible architectural solutions
- Fitness Functions: definition of the performance criteria and use of different analysis tools (fitness functions) to evaluate in an iterative process the performance of each solution
- Optimization: use of an evolutionary multi-objective optimization based on Genetic Algorithms to find within the search space an optimal solution

The optimal form that emerges from such a design approach results from an interaction with a heterogeneous set of climate based data that affect both its energy and structural behavior. In this project, this integrated system was created entirely with the Rhinoceros's plug-in Grasshopper introducing in each phase of the project different add-ons for analysis and optimization. The Grasshopper's add-ons Honeybee & Ladybug (Roudsari and Pak 2013) were used to inform the process with climate data and advanced energy analysis, Karamba (Preisinger 2006) was used to evaluate the weight of the wooden structure while Octopus (Bader and Zitzler 2008) to perform evolutionary multi-objective optimization.

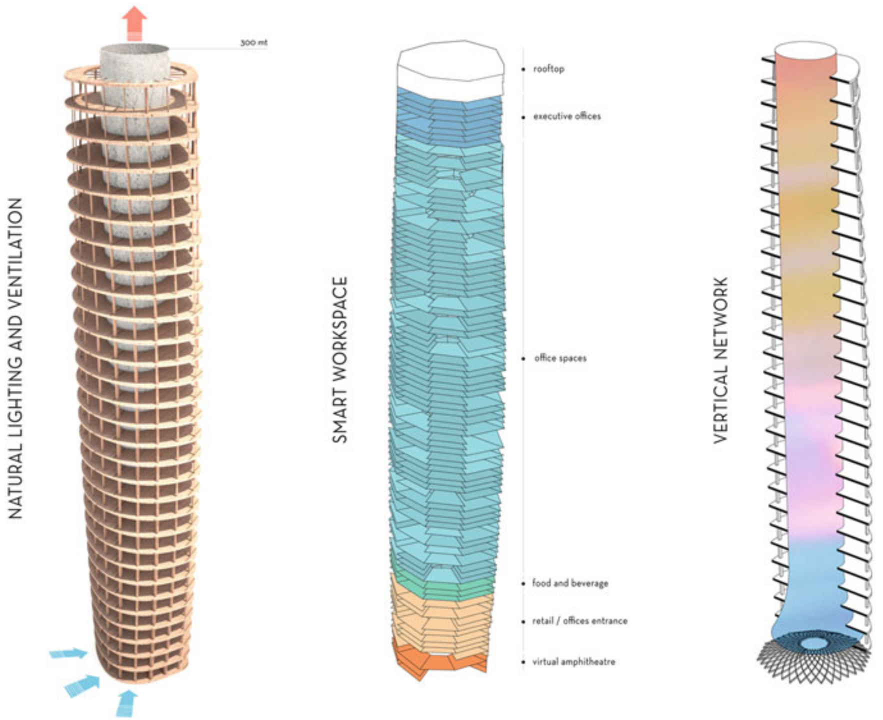

Fig. 8 The adaptive model is composed by three deeply integrated systems: the core, the cluster, and the envelope

4.2 Generative Model: Adaptive Wooden Skyscraper

In the context of computational design, a generative design system is a group of geometrical rules that enables to go from a set of parameters (genome) to geometry (phenotype). This is the phase of the design process in which the designer has more control over the outcome, and it's only "through a well-designed system of rules, that generative design systems have the capability of maintaining stylistic coherence and design identity while generating different designs. (Granadeiro et al. 2013)" In this sense, the proposed free-form organism is composed of three deeply integrated systems: the core, the cluster, and the envelope (Fig. 8). They adapt their dimensions and functions to the context to maximize energy efficiency and comfort.

- Timber Structure: The free formed structure is made of Cross Laminated Timber and Glulam. The use of this renewable material sensibly reduces the carbon footprint of the skyscraper.
- Responsive Core: An artificial intelligence is integrated into the concrete core structure. In addition to its structural and distributive function, it acts as a thermoregulator by controlling temperature, humidity, and air quality.

- Cluster System: The flexible cluster system is capable of adapting to the requirements of smart working by offering a wide variety of spatial solutions.

4.3 Fitness-Based Optimization

The right balance between the three described systems is obtained through an optimization process aiming to maximize energy efficiency and comfort while minimizing structural weight. Indeed, while some characteristics of the architectural organism are defined directly by the designer through the generative model, other qualities are supposed to emerge through a well-defined optimization. Inspired by the evolutionary process, the algorithm used in this research is based on the Hype algorithm of Octopus, a Grasshopper's add-on for multi-objective optimization.

In this project, as in many other architectural projects, it was useful to consider more criteria simultaneously: the weight of the structure, the energy performances, and the visual comfort. However, these are only some of the performances that may interest the designer, and in theory, each parameter that affects the Architect's choices during the design process can be added to the concept of fitness. It remains an open list, and along with the advancement of performance simulation, new criteria and analysis tools can be used to inform this process.

4.3.1 Lightness Through Structural Optimization

The structural system proposed in this project is inspired by the Australia Square Tower designed by Harry Seidler in collaboration with the Italian Pier Luigi Nervi. By moving from a cylindrical-shaped to a free-form structure, this research proposes a reinterpretation of this structural model characterized by a central core, exterior perimeter columns, and sculptural ribbed floors. The decision to liberate the form from his original circular and highly efficient design (Desideri et al. 1979) is related to the desire of obtaining an architectural organism that can be shaped by light.

The optimization process aims to find within the possible geometrical configuration of this structural model the one that implies less use of material. The optimization method encompasses the following steps: (i) for each formal solution, a structural system is defined; (ii) an optimization process finds the optimal cross section for the elements of the structure; (iii) the cost of the structure is calculated starting from its weight; (iv) the cost of the structure is used as fitness in a genetic optimization.

Firstly, an associative logic defines the position of each structural element starting from the free-form shape of the skyscraper (Fig. 9). With the parametric structural engineering tool Karamba, these elements are used, to define a Finite Element model able to evaluate the structural efficiency of each design solution. Then, after the definition of loads, supports, joints, and material properties; the component Optimize Cross Section is used to calculate the optimal cross-sections of the structural elements.

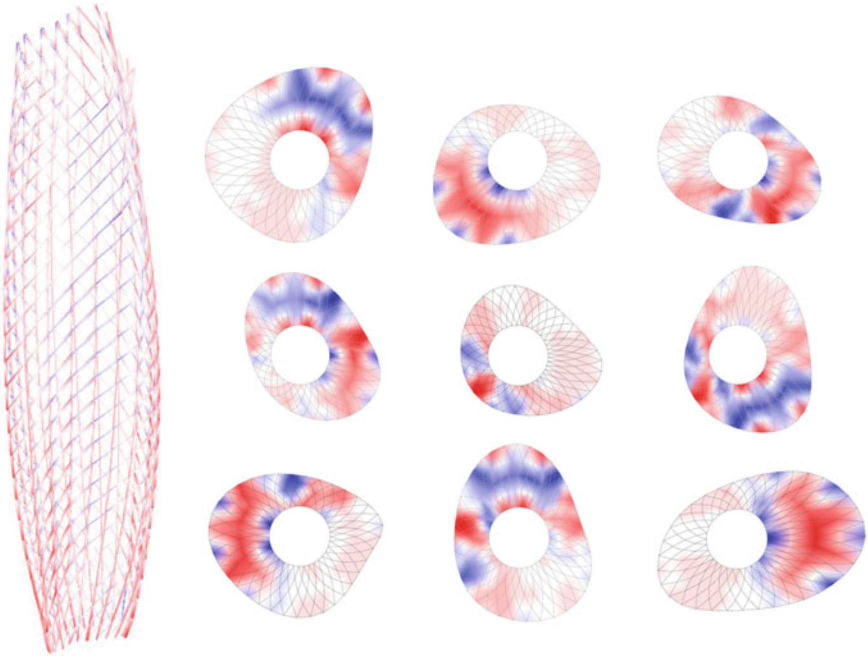

Fig. 9 Structural fitness: CLT slab dimensioning through FEM analysis Karamba parametric engineering

The construction cost is approximated by evaluating the mass of the obtained structure and is used as a performance criteria. By iterate this process for different design solutions the generative model shows great variability in performances, highlighting different structural behaviors. These results are used along with energy performances to inform the design process and are used as fitness in a multi-objective optimization.

4.3.2 Environmental Optimization: Light, Energy and Comfort

With the aim to adapt the skyscraper to its environment the Grasshopper's add-ons Honeybee & Ladybug were used to inform the design process with climate data and advanced energy and daylight analysis. The main goal in this phase was to optimize natural lighting and visual comfort. Whereas, another environmental aspect was the optimization of passive solar energy regulating the contribution of solar gain and shading, depending on the specific climate conditions.

Light strictly related to the office workers well-being becomes one of the major driving forces of this fitness-based optimization. The goal is to reinforce circadian rhythms and reduce the use of electric lighting by introducing natural daylight into space. Appling the LEED (USGBC 2013) guidelines for lighting, this design phase

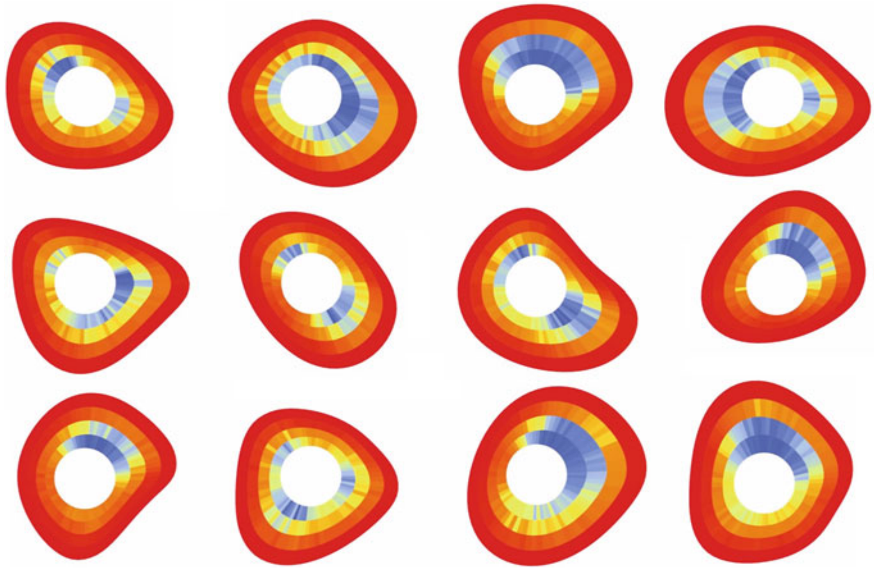

Fig. 10 Fitness variability: daylight analysis for spatial daylight autonomy (sDA) evaluation

is driven by two Annual Daylight Performance Metrics: spatial daylight autonomy (sDA) and Annual Sun Exposure (ASE) (IESNA 2012). The first one defines the lighting autonomy of the space and is evaluated through an annual Daylight simulation conducted with Honeybee and Radiance (Fig. 10); while the second one, is related to glare potential and is calculate through a sunlight hours analysis based on Ladybug. This two value are simultaneously optimized, and different design solutions are tested to maximize sDA and minimize ASE.

The goal of an environmental optimization is to ensure a satisfactory comfort with the minimum use of energy by adapting the architectural organism to his context and his inhabitants. To this end in this research, an energy model is associated to each architectural organism, individual of a genetic population. The fitness of each solution is evaluated with Honeybee by calculating the overall energy consumption as the sum of Heating, Cooling, Lighting. In this phase, through visual scripting, the researchers can define in detail Constructions, Thermal Zones, HVAC systems, schedules and climate data achieving a feasible energy model that can be used in an automated process for environmental and multiobjective optimization.

The result obtained by both lighting and energy analysis are used along with structural performance to inform the optimization and design process. Once again, the variability in fitness highlights the adaptive capacity of the model and the importance of exploring skyscraper generative potential to obtain architectural organism characterized by rational use of matter and energy. In this sense, genetic algorithms support the designer in finding an optimal solution and compare different performance (Fig. 11).

Fig. 11 View from the interior space: double height atrium

5 Conclusion

The innovative techniques of representation introduced by parametric design open countless scenario for further research and experimentation. Wood seems to be a perfect material to engage with this new period of design research, and while concerns with the environmental impact of the building industry push the exploration of alternative structural solutions, a new era for timber technology begins. The built and unbuilt projects proposed in this paper highlight the global explosion of timber towers: a type that has the potential to become central to contemporary architecture. In the 21st century, the importance of skyscrapers will continuously increase, and even if it has been traditionally seen as a building type outside the mainstream of architecture culture, it is destined to ignite the theoretical and artistic debate, becoming the most highly discussed building type of its era.

By looking at the skyscraper as an adaptive organism, designers have the potential to guide the sustainable growth of our cities, developing site-specific solutions to a design problem of international nature. In this sense, generative design and bio-inspired optimization strategies can be used as a mean for bio-climatic design, highlighting the generative potential and adaptive capacity of an architectural model. This design approach, apply surprisingly well to skyscraper design, where it can lead to considerable savings regarding energy and material. Moreover, along with the advancement of performance simulation and building information modeling, this method can be improved to obtain a fully integrated design process that help designer to achieve both performance and aesthetic expression. To conclude, the interdisciplinary approach based on parametric design and evolutionary principles, proposed in this research, demonstrate how designing following the rules of nature can result in the definition of architectural organisms characterized, like natural ones, by lightness, efficiency, and multifunctionality.

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