

An ecology of daylighting: Form follows light and performance follows form

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ABSTRACT

This paper explores how an ecological approach to daylighting can give form to architecture while simultaneously defining the building performance and human experience. A case study profile of Mario Cucinella Architects' recently completed ARPAE (Regional Agency for the Prevention, Environment and Energy) Headquarters in Ferrara, Italy considers the balance between the practical and the poetic, as well as the aesthetic dimensions of ecological daylighting design. Over the past decade, the "science of daylighting," has matured as practitioners and building science researchers have continued to demonstrate measurable benefits of daylighting in the areas of energy savings, carbon and greenhouse gas reductions, increased human comfort, and improved productivity and health. These developments have benefited architects and designers to more effectively integrate daylight with other design and performance issues. Yet, with the promise of scientific and analytical advances, there also lies a risk of too narrowly focusing on daylight parameters that are measurable and empirically defined. An analytic perspective on daylighting design needs to be balanced with the qualitative and experiential dimensions of natural light. The ARPAE project was developed using design methods and tools for thoughtfully integrating daylighting performance with human experience in relation to place, seasons, and time. The paper investigates an ecological approach to daylighting design using interviews and evaluation of qualitative and quantitative assessments provided by the architect to consider the potential of daylighting to simultaneously shape the building and subsequent human experience and design performance.

KEYWORDS: Daylighting, Energy, Sustainable Design

INTRODUCTION

Over the past decade, the "science of daylighting," has matured as practitioners and building science researchers have continued to demonstrate measurable benefits of daylighting in the areas of energy savings, carbon and greenhouse gas reductions, increased human comfort, and improved productivity and health. Great improvements have been made in digital rendering, analysis tools, and an ever-increasing number of daylight metrics, guidelines, and assessment methods. These developments have benefited architects and designers in more effectively integrating daylight with other design and performance issues. Yet, with the promise of scientific and analytical advances, there also lies a risk of too narrowly focusing on daylight parameters that are measurable and empirically defined. An analytic perspective on daylighting design needs to be balanced with the qualitative and experiential dimensions of natural light.

This paper explores an ecological approach to daylighting design in which form, performance, and human experience are inseparable. It considers how daylight is foremost a design issue, and secondarily a question of technology. A case study investigation of the ARPAE (Regional Agency for the Prevention, Environment and Energy) Headquarters in Ferrara, Italy by Mario Cucinella Architects (MCA) reveals how daylight shapes



Figure 1: South and east facades (left); roof under construction (right). Source: (Moreno Maggi Photographer, MCA, 2017)

architectural form and form shapes the resulting experiential and performance qualities and characteristics of architecture (Figure 1). The study included interviews and evaluation of qualitative and quantitative assessments provided by the architect to consider the potential of daylighting to simultaneously shape the building and subsequent human experience and design performance. The building was studied through drawings, diagrams, schematic models, and findings from the technical report. Acknowledging the limitation of studying a single building, the research provides initial insight into the potential of daylighting as a poetic and performance design driver. Cucinella's approach to design seeks to integrate both the poetic and the pragmatic dimensions of daylight by considering natural light as an environmental phenomenon and a dynamic "building material". Daylight has evocative form-giving potential that is intimately related to site, programmatic, performance, material, and experiential dimensions of design. It is an environmental phenomenon and an ephemeral architectural material. Daylight and the changing environmental forces of sun, wind, and weather help us to know "where we are" and "who we are" by rooting us in the ecological phenomena of a particular place, in that climate, and on that site. When coupled with passive solar and bioclimatic design strategies, daylight can reduce energy consumption and provide environmental benefits while enhancing human comfort, health, and well-being. ARPAE demonstrates the intersection of form and performance as the essential design goal, as Mario Cucinella explains: "Form and performance is a relationship. Expressing well the idea of architectural form [as] fundamental to the performance of building and [considered] before technology (Cucinella, 2015)".

1.0 FORM FOLLOWS LIGHT

Early modern architect Louis Sullivan is renowned for his 1896 essay on the "tall office building," in which he penned the famous phrase "form [ever] follows function": "It is the pervading law of all things organic and inorganic, of all things physical and metaphysical, of all things human, and all things super-human, of all true manifestations of the head, of the heart, of the soul, that the life is recognizable in its expression, that form ever follows function. This is the law (Sullivan, 1896, 403-409)". Inspired by the Roman architect Marcus Vitruvius Pollio, who wrote in *De Architectura (Ten Books on Architecture)* about the architectural qualities of *firmitas, utilitas, venustas* or "firmness, commodity, and delight," Sullivan inspired architects to explore the richness, value, inherent beauty, and form-giving potential of fundamental elements of architecture such as structure, materials, construction methods, technology, and program (Sullivan, 1924, 108). In a similar spirit, Alvar Aalto, the renowned Finnish modern architect, cautioned against the exploration of form independent of context: "Only where form arises at the same time as content or in faithful combination with it, as it were, can we speak of a step forward, but then form as a separate element no longer interests us (Ruusuvuori, 1978, 155)". Similarly, Louis Kahn, a contemporary of Aalto, characterized the inseparable relationship between form, design, and program: "Form is 'what.' Design is 'how.' Form is impersonal; Design belongs to the designer. Design gives the elements their shape, taking them from their existence in the mind to their tangible presence. Design is a circumstantial act. In architecture, it characterizes a harmony of spaces good for a certain activity (Lobell, 1985, 28)".

An ecological variation on this theme can be found early in the development of regenerative design theory when landscape architect John Tillman Lyle included the concept "Shape Form to Guide Flow," as one of eleven regenerative design strategies, as Lyle explained: "This principle could also be stated 'flow follows form follows flow.' Energy and material flows occur within the physical medium of the environment, and the medium largely determines the pace and direction of flow. By shaping the medium (the environment), we can guide the flow (Tillman Lyle, 1994, 43)". This principle extends to daylighting design in the ways that form influences the flow of light in its movement, quantity, and quality. The flow of light also shapes form; while the luminous characteristics of natural light inform our perceptions of architectural form and space. The building massing, section, size and placement of windows, detailing of the windows inside and out, and other form-related factors determine how deeply light can penetrate into a space, how light is distributed, and the amount and atmosphere of light.

More recently, Swiss architect Peter Zumthor reflected on the notion that "form follows anything," as Zumthor explained: "In a way I think it's true, form can follow content, it can follow profit, it can follow the truth, it can be used to create presence. . . . Architecture is not about form, it is about many other things. . . . The light and the use, and the structure, and the shadow, the smell and so on. I think form is the easiest to control, it can be done at the end (Zumthor, 2013)". His variation on Sullivan's famous quote suggests that form can arise out of diverse factors such as place, climate, culture, users, activities, and construction. While form may not always be the starting point, it is nonetheless of fundamental importance, as Zumthor clarifies: "But if, at the end of the day, the thing does not look beautiful – and I'm deliberately just saying beautiful here . . . if the form doesn't move me, then I'll go back to the beginning and start again. So you could say . . . my final aim, probably is: The Beautiful Form (Zumthor, 2012, 71-73)". Form and light are inseparable from the activities and purposes of architecture. Whether poetic or pragmatic in nature, an inherent beauty and aesthetic comes from finding the appropriate form for the architectural context and aspirations.

2.0 LIGHT AND THE QUALITY OF PLACE

2.1. Ferrara and the Po River Delta

Located in the Emilia-Romagna region of northeastern Italy, the new headquarters for the ARPAE headquarters is a model of ecological innovation. The office building is designed to demonstrate the ways in which architectural form can integrate with climate-responsive passive strategies, innovative systems, and new construction methods to create beautiful architecture while meeting the highest sustainable design standards for performance.

2.2. Bioclimate and Italian Light

Located on the outskirts of Ferrara, the open suburban site affords excellent access to sunlight, wind, and views. As a humid temperate climate, precipitation and high humidity are common, with relative humidity averaging 60 to 70 percent in the summer months and 80 to 90 percent in the winter. Precipitation varies throughout the year, with light to moderate rainfall greatest in May and least likely in October. The location experiences only occasional winter snow. The average precipitation ranges from a minimum of 11.6 millimeters (0.45 inches) in March to a maximum of 39 millimeters (1.58 inches) in October (World Weather Online, 2017). Temperatures are cool in the winter and hot in the summer, with an average low of 2.5° C (36.5° F) in January and an average high of 31° C (87.8° F) in July (WeatherSpark.com, 2017). Skies are clearest during the summer months and most overcast in the winter. Wind direction is variable throughout the year.

3.0 LIGHT AND THE DESIGN INTENTIONS

3.1 Defining the Ecological Office Program

Designed to meet the expanding office and laboratory needs of ARPAE, an environmental protection agency, the program brief emphasized sustainable design, technological innovation, ecological performance, and health and well-being. Cucinella designed the headquarters as a “model ecological office building” to celebrate dynamic luminous and thermal conditions and to challenge the status quo uniform approach to human comfort: ARPAE is about change. . . . [In the past,] the future of technology and innovation was a closed building with air conditioning and always the same temperature and the same light. In another office building we surveyed 160 people with a questionnaire. The results were impressive. They cared most about daylighting and the natural variation of [light] intensity. Artificial light has no variation. Daylight is part of the psychology, an emotional part of the story, a bright light and a cloud, it can change completely in intensity (Cucinella, 2015). Rather than viewing changing light and thermal conditions as problems, Cucinella designed an office building that fosters varied conditions to improve occupant satisfaction and performance.

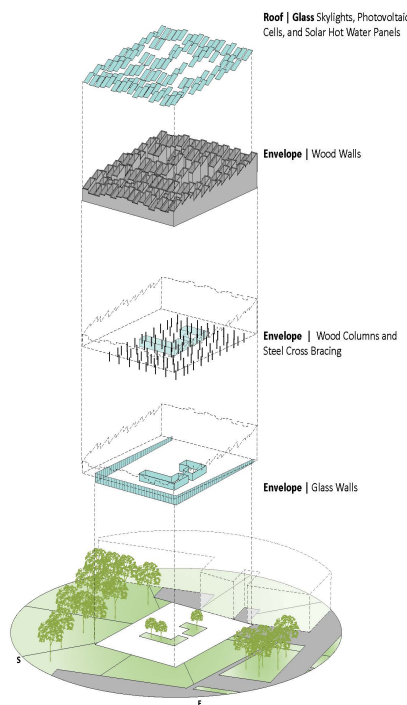


Figure 2: Massing and structure diagram. Source: (Fiona Wholey and Author, 2017)

Cucinella describes “form and performance” as an interrelationship that is the driving design concept at ARPAE: “Architectural form creates natural performance. . . . Combining the idea of daylight and natural ventilation gives extraordinary performance. The only way to improve comfort in summer is with cooling to increase air change and to move air and transport humidity (Cucinella, 2015)”. The summer goal was to mediate the high relative humidity and temperatures with natural ventilation and to provide daylighting without solar gains. The winter goal was to harvest solar gains for passive heating, while providing luminous and thermal control in office and laboratory spaces (Figure 2).

3.2 Fostering a Site Relationship

To respond to today’s ecological challenges, Cucinella argues that architects need a more empathetic understanding of the site and other living things:

To be empathic is to have a relationship with someone else or a site . . . I call it ‘creative empathy.’ Showing empathy is an attitude. Using your mind and body to try to understand what is outside [of you]. Empathy is the capacity to listen, to create a relation. The first idea of the climate condition is to make an interpretation of the shape and angles of the building. I try to find in this information clarity . . . to influence and make the building from empathy with the site (Cucinella, 2015).

While always looking towards the future, Cucinella also seeks inspiration from bioclimatic design innovations that have been honed over thousands of years in vernacular architecture, which are often inherently empathic to place, culture, and nature. ARPAE provides a fresh interpretation of the

traditional courtyard building by combining iterative wind chimneys with exterior and interior sidelighting to improve luminous and thermal performance and provide views to the site and gardens (Figures 2 and 3).



Figure 3: Interior courtyard (left); view to courtyard under construction (right). Source: (Moreno Maggi Photographer, MCA, 2017)

3.3 Enhancing Aesthetic and Sense Experiences

The design of ARPAE balances the practical dimension of daylight and the aesthetic and experiential opportunities. While mindful of addressing daylight requirements for visual comfort, glare, and illuminance targets (discussed in section 5.2), MCA also consider the role of beauty, aesthetics, health, and well-being in office design. Cucinella explains: “In the last 20 years architects have tried to make office space more efficient. They are so efficient that people are unhappy. If you look at the history of architecture, it was about quality. People are at work 8 to 10 hours [per day]. We need to take into account that they pass more time in the office than at home. We need to improve the office quality (Cucinella, 2015)”. Daylight, natural ventilation, and passive strategies invite occupants to experience the changing moods of the day and seasons. Interior and exterior views provide visual relief and connections to the landscape, while operable windows and adjustable shading enable occupants to individually tune their environment. The exposed wood structure and the healthy materials, finishes, and furnishings create a friendly and relaxed atmosphere that invites occupants to touch and interact with the envelope, space, and gardens (Figure 4 and 5). Human aesthetic and sense experiences of architecture have been design priorities throughout history, as Cucinella explains:

I think of the Gothic architects, we see how much these people made an effort to make the wall so thin, to make colored glass to bring light inside, to create this emotion. . . . ARPAE’s new idea of beauty and sustainable design is not an illusion. It’s something very real. A connection, a relation to daylight and ventilation and shape. My concept of beauty is something invisible; but there is a part that is visible, that is aesthetic, like the character of a person (Cucinella, 2015).



Figure 4: Views into the courtyards and site while under construction: (Moreno Maggi Photographer, MCA, 2017)

4.0 LUMINOUS DESIGN STRATEGIES

Sited south of the existing office building, the rectilinear mass of the new headquarters is oriented to the southeast. A new garden entry creates a transparent connection between the old and new buildings to house the lobby and reception area. The single-story plan comprises a series of offices and labs organized around two L-shaped and interconnected garden courtyards at the heart of the building. In contrast to an open-office plan, Cucinella organized the building as a series of autonomous rooms linked by circulation routes and gardens. Each office and laboratory space has visual connections to either the outside landscape or the

interior gardens and contains one or more roof monitors or “chimneys” to provide stack ventilation and daylighting. A seemingly “thick” building plan is transformed by the courtyards into a series of thinner spaces with both toplighting and sidelighting in each space. Borrowed light, views, and air are provided through interior and exterior operable glazing (Figure 5).

The building envelope uses two nested-façade systems, with recessed glazing at the ground level and an overhanging wood-clad envelope on the upper portion of the façades and roof monitors. The upper façade acts as a “solar visor” to shade the recessed glass during the warm seasons and to create a sheltered circulation space on the exterior of the building. Less shading is provided on the south to capture low winter sunlight for passive heating and daylight. Roof monitors extend beyond the glass envelope to admit light and air to the exterior circulation paths (Figure 6). Cucinella calls the roof “a climatic moderator,” and explains the essential ecological role of the chimney monitors: “The roof of the building, the so-called fifth façade, is the strongest design feature of the project. A series of chimneys give to the building a strong architectural identity while satisfying the technological requirements of the brief. The chimneys are skylights that filter natural light, promote natural ventilation and reduce the need for mechanical cooling (Mario Cucinella Architects, 2015, 1)”. The undulating rooftop monitors vary in height to avoid shading adjacent monitors and to respond to the east to west solar movement.

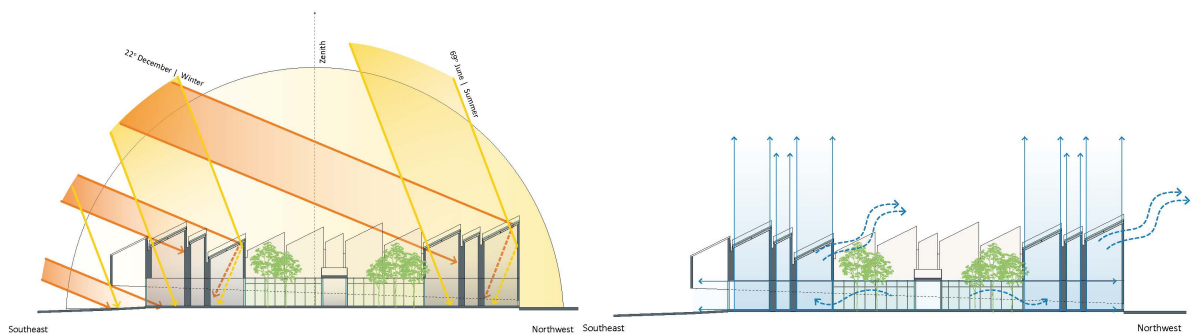


Figure 5: Sections illustrating façade overhangs and roof monitors. Source: (Fiona Wholey and Author, 2017)



Figure 6: View of layered façade (left); roof under construction (right). Source: (Moreno Maggi Photographer, MCA, 2017)

5.0 QUALITATIVE AND QUANTITATIVE DESIGN PROCESSES

5.1 Qualitative Design Methods

MCA employ a variety of in-house methods and tools to support the early design decisions regarding the building siting, massing and section. The early design process includes diagramming, rendering, physical models, daylight models, and seasonal solar massing studies to assess daylight access and shading to explore massing, section, and varied roof forms and configurations. Cucinella emphasizes the importance integrating qualitative and quantitative intentions and methods into the early design process: “The way we design makes the aesthetic of the building...Using early design tools we bring that information from the beginning. I’m not an engineer, but I can simulate something at an early stage to work with daylight and suggest to the engineer how to integrate natural and artificial light (Cucinella, 2015).”

Cucinella encourages architects to reclaim more authority over the early integration of design and performance. He argues that the design process and performance testing are interrelated, and set the early trajectory of the project. Daylight models are an essential design tool used to study the building siting, exterior building massing, as well as the interior quantity and quality of light under varied sky conditions. Cucinella explains: “Daylighting is something you can learn using models. Start with a room and play with materials, shiny, matte, different intensities of color. Use a sensor to see how much daylight influences the quality and quantity of light inside the room (Cucinella, 2015)”.

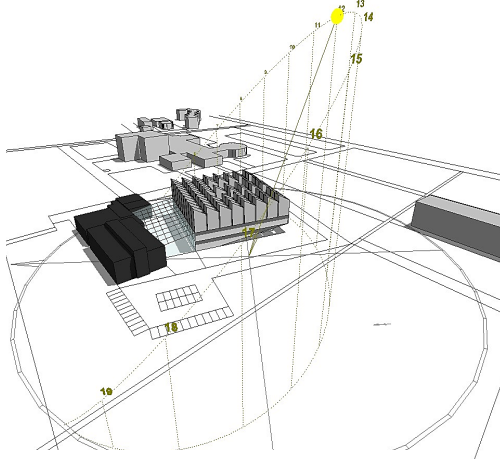


Figure 7: Example site massing solar diagram.
Source: (MCA, 2016)

Despite sophisticated digital design tools, Cucinella stresses the critical role of simple physical models in understanding the design of daylighting. Given accurate geometry, room surface reflectance, and material properties, designers can accurately experience the quality of light while evaluating the illuminance levels and distributions. Cucinella emphasizes that the physical models are unique in allowing designers to have a tangible experience of light while and obtaining an accurate measure of illuminance levels in the space (Figure 8):

We always start working with real models to understand and learn by experiencing the quality of light. You can learn so much from a box with a hole. You can see and transform the quality of light inside by changing color, changing surface, changing reflection. You can see the light and 3-D architectural elements. We always make physical models, especially daylight models (Cucinella, 2015).

Early design proposals for ARPAE were later refined using iterative quantitative analyses to assess the effectiveness of the daylighting and ventilation strategies.

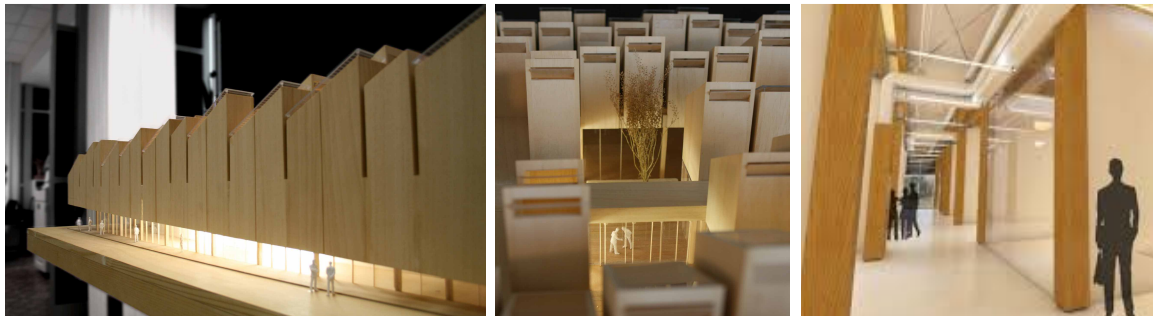


Figure 8: Example early daylight massing models and interior daylight studies. Source: (MCA, 2016)

5.2 Quantitative Design Methods

In later stages of the design, MCA worked with Roberto Zecchin, Adileno Boeche, and Andrea Fornasiero and colleagues at Manens-Tifs S.p.A, a leading engineering firm in Italy, to conduct bioclimatic studies and to further assess and refine the daylight, ventilation, and thermal design performance. Manens-Tifs developed a sequence of rigorous quantitative analyses to complement the qualitative in-house studies. Quantitative assessments provided essential insights into the architectural form and response to bioclimatic forces, while supporting an informed discussion to refine the daylighting design quality and performance.

Daylighting analyses were developed using RADIANCE software to assess the daylight factor (DF%) and illuminance levels (in lux) on the workplane at .75 meter (2.46 feet). Ten room locations were evaluated to compare the daylight performance in the four cardinal directions (north, east, south, and west) as well as interior locations along the courtyard. The studies evaluated the minimum, maximum, and average daylight factors in the select rooms to assess the room form and glazing transmission characteristics. An example illustration from the daylighting study is shown in Figure 9, which verifies that adequate daylight is provided on the workplane with an average daylight factor of 1.75-3.25% and illuminance levels of 350-550 lux. Additional daylight studies systematically evaluated the various combination of perimeter sidelighting, interior sidelighting from the courtyard, and toplighting to refine the building form and glazing specifications. Findings from Manens-Tifs were essential in design refinements: “The analyzes were carried out for several cases, in

order to highlight the importance of the contribution of perimetrical windows and zenith glazing of the chimneys of light, taking into account some possible scenarios for the latter. Particular attention was paid to the importance of skylights, whose correct overall light transmission factor, taking into account shielding, is decisive for the success of the maximum natural lighting of the rooms” (Manens-Tifs S.p.A. 2009, 83-89).

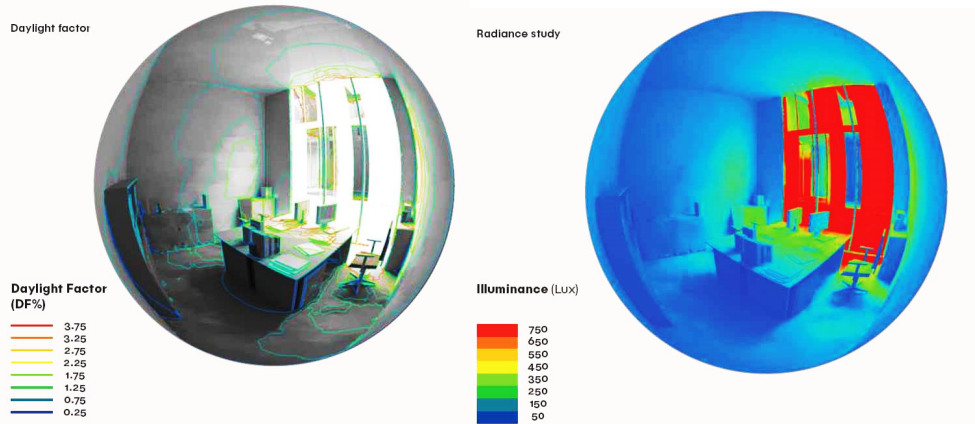


Figure 9: Radiance illuminance studies to assess daylight performance. Source: (MCA: Manens-Tifs S.p.A., 2009)

Natural ventilation was analyzed using Fluent 5.5 computation fluid dynamic software to evaluate the sectional contours of temperature in kelvin (k). Studies evaluated the direct average solar radiation in the solar chimneys (room monitors). Assessment of the vertical distribution and sectional contours of the room and chimney temperatures were conducted during the winter period (9:00-17:00 from December 1-February 28) as well as the summer period (8:00-19:00 on June 1-August 31). An example of the vertical distribution of temperature is illustrated in Figure 10. Findings from Manens-Tifs confirmed the effectiveness of the solar chimneys:

“Stratification of temperatures does not take on too much marked characteristics, the action of a fan in conjunction with the presence of the solar chimney is useful in the de-stratification of the air inside the rooms and contributes to the heating of the occupied area...The flow of air coming from the lower part and coming out of the opening at the top avoids the accumulation of heat in the upper part of the structure” (Manens-Tifs S.p.A. 2009, 66).

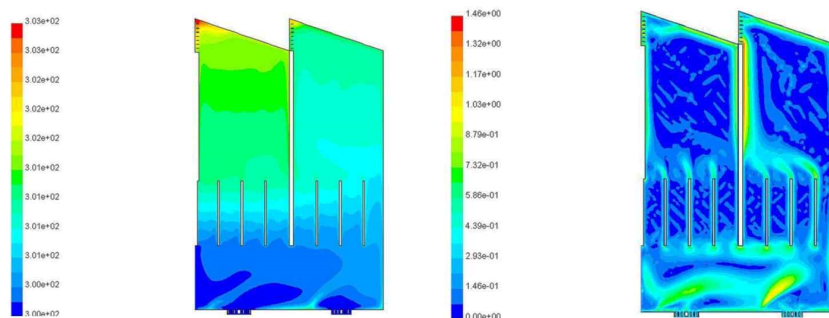


Figure 10: Computational fluid dynamics study of ventilation performance. Source: (MCA: Manens-Tifs S.p.A., 2009)

5.3 Light Shaping Form and Performance

Mario Cucinella set out to define a new model of ecological office building that responds to the particular conditions of site and climate; supports health and well-being of the occupants, and meets the highest standards of sustainable performance. The ARPAE building form and section are unique in combining three daylight strategies: 1. Exterior sidelighting, 2. Interior courtyard, and 3. Rooftop chimneys with skylight monitors to seasonally integrate natural light and ventilation. This hybrid configuration of exterior and interior sidelighting coupled with toplighting provides daylight and natural ventilation to every space in the office building. The shape of the plan, massing, and section are integral to the thermal and luminous comfort and energy performance of the building, as Cucinella clarifies: “Shape is part of performance; that’s why I like ARPAE. We are really building a bridge with our past when buildings dealt with nature with no energy. That was the job in the past and now (Cucinella, 2015)”. During the summer months, the combined wind chimney and daylight monitor, sidelighting, and self-shading building form are architectural strategies to reduce cooling loads. Winter strategies include direct solar gains, daylighting to reduce electric lighting loads, and high-performance envelope and glazing systems. A geothermal heat pump is connected to a radiant distribution and heat recovery system to optimize thermal comfort throughout the year. Additional water

savings are realized through a rainwater system that collects runoff from the roof to reuse for heating, irrigation, and greywater. Renewable energy include solar hot water heating and a 201 sq.m (2,164 sq.ft) photovoltaic system. MCA estimates that bioclimatic, passive design, and renewable energy strategies, along with high performance systems, reduce summer and winter energy consumption by 30 percent and 40 percent respectively as compared to a similar-sized conventional building (Mario Cucinella Architects, 2015,1). The estimated energy profile for winter is 35 kWh/sq.m (11.1 kBtu/sq.ft), while summer is 50 kWh/sq.m (15.9 kBtu/sq.ft). High performance mechanical systems are estimated to provide a carbon reduction of 85 percent at 3 kg CO₂/year (compared to a standard building) (Mario Cucinella Architects, 2015, 1).

CONCLUSIONS

Architectural form, performance, and aesthetic experience are at the heart of an ecological approach to daylighting design. Architecture is not a static object, but rather a dynamic relationship with site, climate, and users. Cucinella uses architectural form, rooftop chimneys, courtyards, and a layered envelope to celebrate seasonal changes in luminous and thermal conditions and to invite visual and physical interactions between the users, architecture, and nature. The ARPAE headquarters elevates the promise of the ecological office, inspires a new definition of sustainable design excellence, and raises the bar for all building types, as Cucinella suggests: "Each building has the potential to redesign the surrounding natural, cultural, and socio-economic systems. Buildings can recreate an intimate relationship – a 'creative empathy' – to link places and their inhabitants . . . that are enriching and enabling environments for life and work (Cucinella, 2012)". While this research is limited in scope to one project, it suggests the potential of an ecological approach to daylighting in which "form follows light and performance follows form". As a new ecological model for office buildings, five daylighting design strategies emerge from the case study:

1. Expand Performance Programming: All scales of design were considered through the lens of performance, including measurable issues such as illuminance levels, air flow, annual energy consumption, and carbon emissions along with intangible qualities of health and well-being, beauty, and aesthetics.
2. Rediscover Site and Climate as Design Drivers: The first level of daylight and architectural response is to site and climate, with the integrated design strategies arising from context. Vernacular approaches to integrating daylight, passive heating, and natural ventilation are reconsidered from a contemporary perspective.
3. Allow Form to Follow Daylight: Cucinella ask designers to consider three key issues: How is natural light architectural? How might light shape form? And how might form shape light?
4. Claim Authority over Early Testing and Analysis: Early iterative testing and assessment are key to the integration of form and performance, with a variety of design methods and qualitative and quantitative metrics employed, from simple daylight models to sophisticated computational analyses and large-scale mock-ups.
5. Verify that Performance Follows Form: Architectural form is found through the meeting of design aspirations, site and programmatic forces, desired qualities, and performance goals. Just as a sculptor shapes a piece of marble to express a desired intention, so too an architect sculpts the building massing, plan, section, envelope, windows, and interior forms to create a desired luminous environment.

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