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Article

Dialectic Form Finding of Passive and Adaptive Shading Enclosures

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Abstract: Form finding describes the process of finding a stable equilibrium shape for a system under a specific set of loads, for a set of boundary conditions and starting from an arbitrary initial geometry. However, form finding does not traditionally involve performance constraints such as energy-related criteria. Dialectic form finding is an extension of the process integrating energy-related design aspects. In this paper, dialectic form finding is employed as an approach for designing high performance architectural systems, driven by solar radiation control and structural efficiency. Two applications of dialectic form found shading enclosure structures, a passive and an active one, are presented. The first application example is a site-specific outdoor shading structure. The structure is based on a louver system designed to provide protection from ultraviolet radiation over a pre-defined target only when required, promoting natural lighting and ventilation. The second application example is a shape-shifting modular façade system that adapts its opacity in response to environmental fluctuations. The system can thus improve the environmental performance of a building. Moreover, the system explores elastic deformations for shape changes, reducing actuation requirements. These examples highlight the potential of the dialectic form-finding strategy for the design of high performance architectural integrated structures.

Keywords: shading; active; passive; form finding; numerical; physical

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1. Introduction: Relevance and Context of Shading Enclosures

A building enclosure, a physical system separating the outdoor from the sheltered (mostly interior) environment, is not just a barrier against unwanted exterior influences but it can also be a selective climate filter. This enclosure can exclude unwanted effects while admitting desirable ones, either passively or actively. Therefore, a key function of the building enclosure is shading. In this study, shading reflects a barrier function against harmful and disturbing solar radiation only, while allowing as much desired natural light and ventilation as possible. For shading design, the first task is to determine when solar radiation should be excluded. This task is driven either by human health considerations, in outdoor structures, or an energy consumption rationale, in building skin systems.

Outdoor health considerations are typically related to solar health hazards. 1.3 million Americans are diagnosed with skin cancer annually, currently representing more than 50% of all cancers in the US [1]. Childhood exposure to the sun's ultraviolet (UV) light substantially increases the risk for skin cancer as an adult. Primary prevention strategies include: (i) increasing awareness in individuals and (ii) implementing preventive measures such effective built shading [2].

The energy consumption rationale relates to the causes of climate change and the risks of energy-dependency and reliability as well as global population growth. According to the United States Department of Energy, buildings in the USA were responsible for 41% of the primary energy consumption in 2010, with 75% of that energy generated by fossil fuels [3]. Space heating (22.5%), cooling (14.8%), and lighting (14.4%) are the dominant energy uses, totaling close to 50% of all energy consumed. In commercial buildings, lighting alone in 2010 accounted for as much as 60% of the electricity usage. These numbers illustrate that energy, consumed in the operation of a building, has a significant impact on the amount of produced CO_2 emissions and the US geo-political energy-dependency and reliability [4]. Global warming effects, urban populations, and the number of energy-intensive activities in cities are all projected to increase. These trends, as well the large size of buildings and their long service life, underline the importance of the energy-efficient systems presented in this paper. Specifically, shading enclosures are core inter-actors between outside weather conditions and the building's sheltered environment [5] which significantly affect space heating, cooling and lighting [6,7] and can effectively address these 21st century societal challenges.

This paper focuses on dialectic form finding as an approach for designing high performance architectural systems, driven by solar radiation control and structural efficiency. Solar radiation control is performed by identifying an appropriate built shape, passive or active, through dialectic form-finding. Integration is very much part of the presented methodology: no distinction is made between the structural and thermal performing elements, and no hierarchy is imposed. Hierarchy is a rather conservative design strategy that divides a complex problem into a series of secondary simpler questions that can be easily resolved with pre-determined solutions. Traditionally, a design approach for shading systems focuses only on thermal and visual efficiency [8–11]. The novel shading enclosures presented in this paper could not have been achieved using this conservative design method. By integrating and optimizing the system, the enclosure becomes multi-functional acting both as a climate filter and structure.

The remainder of this paper is organized as follows: in Section 2, a literature review of the state of the art of climate building enclosures is presented. The concepts behind the dialectic form-finding methodology are explained in Section 3. In Sections 4 and 5, this approach is tested, validated and evaluated for two novel shading enclosures; one passive and one adaptive. Conclusions and further discussion are presented in Section 6.

2. Literature Review on Climate Building Enclosures

Most building enclosures in the USA are designed to shelter and protect their occupants by making the indoor environment insensitive to its exterior surroundings. Consequently, an awkward amount of mechanical and electrical systems needs to be installed, run and maintained for conditioning this environment through heating, cooling, ventilation and artificial lighting. Although this design philosophy might create a productive and pleasant space, this realization occurs at the expense of energy consumption and, hence, the use of natural resources. In contrast, ancient vernacular and bioclimatic architecture considers the outdoor environment as a design driver in the building enclosure design process [12]. In this respect, the role of the building enclosure becomes important as it is at the interface between the indoor and outdoor environment. Moreover, enclosures in purely outdoor environments are crucial for human health: built shading has been extensively outlined from a medical perspective [13–16] as an effective prevention strategy to mitigate health hazards. However, commercial outdoor shading enclosures are mostly driven by uniformity ("one design fits all") and often fail to cast shade over the desired target-shade area. Additionally, as in the case of flexible solar sails and tents, they often trap hot air, perform poorly under strong winds, and provide improper storm water runoff. Consequently, advantages in limiting material use are negated by their lack of function. Novel approaches are thus required for the design of efficient outdoor shading enclosures that: (i) protect from UV radiation throughout the entire year and (ii) allow activities beneath and around the structure to go on uninterrupted [17,18]. The recently completed Metropol Parasol (Seville, 2011, Jurgen Mayer) and Cervantes Theater (Mexico City, 2012, Anton Gracia-Abril) projects show the potential of large scale louvered structures to enhance the urban quality of public spaces in a historic context. Two design approaches for low-energy building enclosures and efficient outdoor enclosures have emerged: a passive and an active one [19–22].

2.1. Passive Enclosures

To moderate the internal environment, building skins have been designed, adopting passive strategies [23,24]. The concept behind this approach is that the enclosure itself copes with regulating the internal and external variables. By choosing factors such as shape (*i.e.*, surface-to-volume ratio and orientation), fabric (*i.e.*, shading, surface qualities, thermal insulation and mass), fenestration (size, position, orientation of windows, glass and its quality, external shades) and air tightness, the building enclosure passively controls the thermal exchange between the outside and the inside environment [25]. These factors are static building enclosure attributes: they cannot change in response to variable meteorological conditions, occupancy and comfort wishes. Most research in this domain has focused on how a single or a combination of specific components (including walls, fenestration, roof, foundation and external shading devices) can affect the internal thermal environment of a building. For a complete overview of the passive envelope components the reader is referred to [26]. The advancements in the domain of self-shading buildings, whose exterior fixed surfaces shade each other, are of particular interest to this paper. For example, a numerical algorithm was developed which generates the shape of a building for an enclosure to be shaded over a designer-defined period of time [27]. The research question arises to what extent a passive large span shading enclosure can be developed to effectively exert solar radiation control while also exhibiting structural efficiency. This research question is addressed in Section 4.

2.2. Adaptive Enclosures

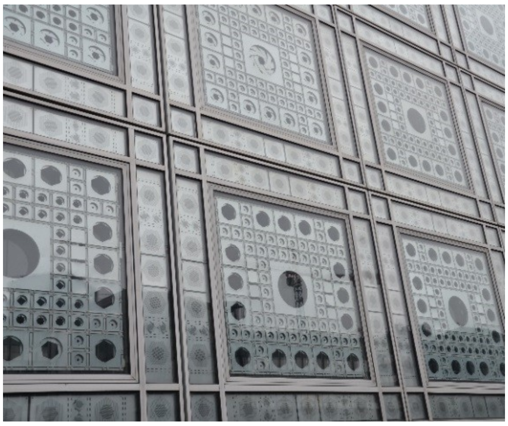
On the other hand, adaptive building enclosures can offer opportunities to exploit the climate and user comfort variability and facilitate the change from an *artificially produced* to a *negotiated* indoor climate [28]. The adaptability of the façade can manifest itself at a micro or a macro scale [29]. At the micro scale, the adaptability can be displayed in the changes of the thermo-physical or opaque optical properties of the enclosure [30,31] such as the light transmitting properties of the material. Switchable windows can adjust their optical properties to modify indoor lighting levels and control solar energy. The most recent developments in micro scale adaptive building enclosures focus on light redirecting properties [32] and enhanced spectral selectivity [33,34].

At the macro scale, the adaptability of an adaptive dynamic building enclosure is perceived in changes in its configuration via observable motion of its parts. On the one end of the spectrum, various flowing media in facade components have been investigated including phase changing materials [35], foam bubbles [36] and flow of air [37]. At the other end of the spectrum, changes in the enclosure's configuration have been realized through moveable parts. Movable shading systems were found to reduce the building energy demand while improving indoor thermal and visual comfort conditions significantly [38]. These enclosures often integrate structural elements along with sensors, actuators, and processing capabilities, resulting in efficient building facade designs [39]. However, these systems often must respond to and adapt to many variables.

One of the first well published adaptive dynamic building enclosures, shown in Figure 1, was based on an array of iris shutters and an associated set of rods, pistons and controls to induce a response in the building enclosure to changing weather conditions [40,41]. Due to the overall complexity of the mechanical system, it failed to work after a short time. Today most adaptive façades (such as the recent solar shading dynamic Al Bahr modular screen, Abu Dhabi, 2012, Aedas) are still based on mechanical, electrically-driven systems. Such facade modules depend on mechanical hinges, multiple actuation devices and controls [42]. The sliding and rotating components of the hinges require regular maintenance, component replacement and out-of-operation costs [43]. Adaptive modules with multiple actuators (such as servomotors or hydraulic pistons) may require perfect synchronization, to avoid residual stresses building up, in addition to well-defined maintenance and replacement schemes, to eliminate large out-of-operation costs. From a design perspective, the engineering of such shape shifting modules is often dictated by practical hinge and actuator related constraints such as allowable forces, available sizes and energy consumption [44] rather than energy related performance criteria.

By considering the analogy of the building façade as a surface that breathes, much like the pores in a skin, physical prototypes of systems have been proposed that make a building enclosure multifunctional and adaptive, while using minimal operational energy. Responsive hygroscopic [41] and bimetallic [42] building façades adapt the porosity of their enclosure (and hence cross-ventilation) to weather conditions through the material response to the ambient relative humidity and temperature, respectively. Other design inspiration for the development of adaptive dynamic shading enclosures, has been successfully distilled from plant movements [45,46]. Building upon the concepts of these precedents, this paper demonstrates an approach that integrates and optimizes a high performance system, so that the shading enclosure acts as a climate filter, structure and actuation component. This methodology is elaborated upon in Section 5.

Figure 1. (**a**) This adaptive façade (Institut du Monde Arabe, Paris (France), 1987) provided an impetus for further development of dynamic building enclosures; (**b**) An array of shutters in the same façade shown in different stages of deployment.



(**a**)

(**b**)

3. Methodology: Dialectic Form Finding of Integrated Systems

Vertical, horizontal or egg-crate shading design for solar radiation control traditionally takes a purely geometrical approach [25] and ignores structural (and kinematic) efficiency. To develop high performing shading enclosures, the approach taken in this paper uses numerical form-finding techniques, which originate from the solution of structural challenges and combines them with constraints, set by solar radiation control requirements. Traditionally, form-finding is a forward process in which parameters are directly controlled to find an optimal geometry for a system which is in static equilibrium for specified loading and boundary conditions. As a result, the obtained shape exhibits material and structural efficiency. Numerical methods exist to solve this static equilibrium problem without requiring material properties (such as force density [47] or thrust network analysis [48]) or by incorporating (material) stiffness (such as dynamic relaxation [49], particle spring [50] or non-linear finite element (FE) approaches [51]). The applications presented in this paper employ a particle spring technique (Section 4.1) and a non-linear FE method (Section 5.2).

Structural form-finding does not usually involve energy-related constraints. The methodologies presented in this paper, entertain a dialogue between structural form and other design drivers related to solar radiation control. This approach is referred to as *dialectic form finding*. The word *dialectic* stems from the Ancient Greek and refers to a method of argument for resolving disagreement. In the context of this research, it stands for the resolution and/or integration of competing (and sometimes conflicting) design drivers through a rational engineering approach. The dialectic form-finding strategies presented in this paper are thus an extension of the traditional structural form-finding process integrating energy-related constraints of shading.

The dialectic form-finding approach differs from optimization methodologies presented by other researchers [52,53] that allow for exploration of the design space while varying structural form, thermal comfort and daylight. Basically, optimization is an inverse process in which parameters are implicitly/indirectly optimized to find the geometry of a structure such that an objective function or fitness criterion is minimized. One can optimize for multiple objectives. In this case, the objectives are evaluated based on their importance, either a priori using weightings or a posteriori by exploring the Pareto front.

To showcase the dialectic form-finding methodology, this paper presents the development of two shading enclosures. The first application is the design of a passive critical UV radiation shading louvered grid shell as a large span outdoor structure (Section 4). The second application focuses on the design of a dynamic shell shading module for an adaptive dynamic building façade (Section 5).

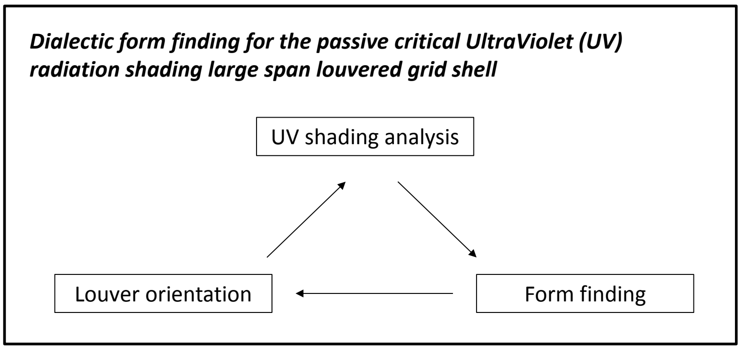
4. Application 1: A Passive Critical UV Radiation Shading Louvered Grid Shell

The dialectic form-finding approach for integrated shading enclosures is first demonstrated by applying it to the design of a large-span, louvered, grid shell system that passively mitigates the harmful effects of UV radiation exposure. Site specificity (set by solar zenith angle, earth-to-sun distance and the site's total ozone) as well as both structural and shading efficiency are the key characteristics of the proposed structure as its shape and louver orientation are defined to provide shade only when required. These characteristics are in sharp contrast with those of most commercially available shading systems (such as solar sails) which are not designed for a specific geographic location and fail to shade effectively.

4.1. Numerical Dialectic Form Finding Bounded by UV Radiation Control Criteria

The dialectic form-finding process, illustrated in Figure 2, integrates three tasks: a UV shading analysis and a form-finding and louver orientation procedure. The UV shading analysis provides the critical solar positions, while the form finding and louver orientation procedures define an appropriate global shape and element orientation respectively.

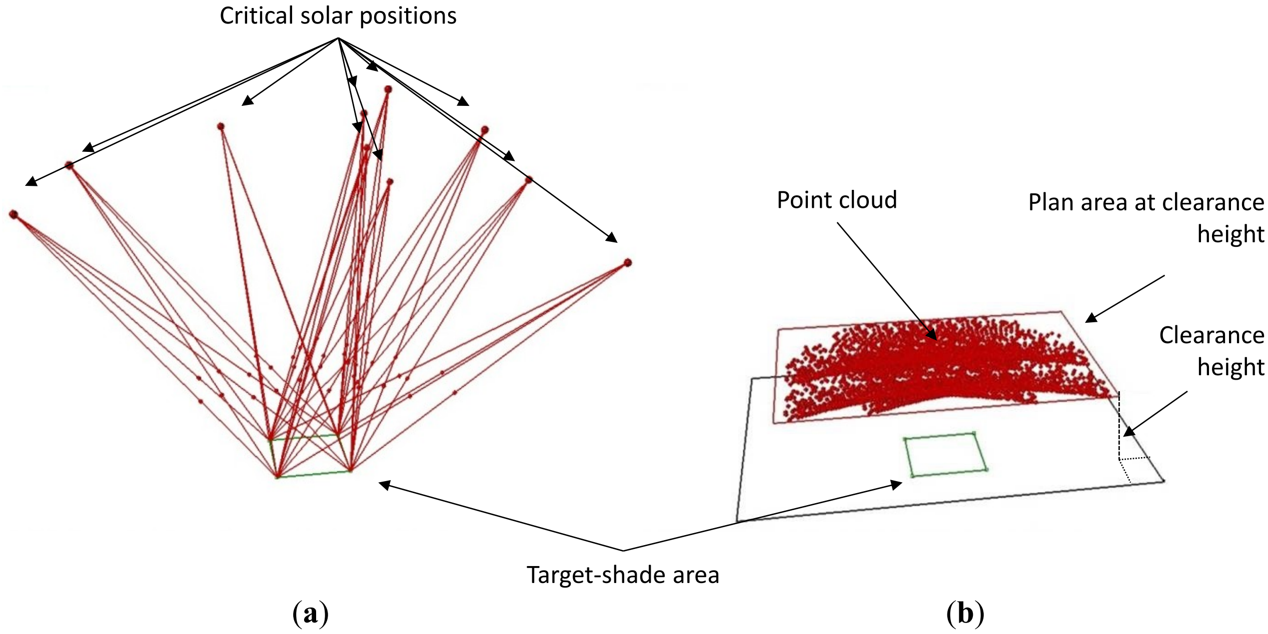
Figure 2. Illustration of the iterative integrated aspect of the dialectic form finding for the passive critical UV radiation shading large span louvered grid shell.



4.1.1. UV Shading Analysis

Unwarranted UV radiation exposure results in various health hazards for humans. The capacity of an enclosure to effectively shade an outdoor area depends upon its geographical location, and more particularly on the solar zenith angle, the earth-to-sun distance and the total ozone concentration, specific to the site [13]. This site specificity and time dependency is ignored in commercially available shading systems. Furthermore, traditional shading structures, such as fabric structures, are usually negated by inadequate functionality since they often trap hot air beneath them and cannot resist high wind loads. For shading fixtures that can be adapted to changing solar positions, such as rotating parasols, damaging UV radiation levels beneath them can be sometimes be up to 84% of that of full exposure during autumn and winter months [13]. Adaptable solutions may also not be as practical for large span roofs. The US Environmental Protection Agency states that health risk starts at a UV Index of 2.5 and above [54], where protection such as built shade should be sought. To determine all the associated critical solar positions that must be shaded throughout the year, their UV Indices over a user-defined target-shade area can be identified using a UV Index algorithm, proposed by [55]. Typically, shaded outdoor recreational areas (e.g., playground, recreational areas, *etc*.) rely on a plan target-shade area (e.g., the outline of a basketball court) which cannot be obstructed with structural elements. Using a shading analysis and a structural form-finding technique, the geometry of a long span thin-shell system can be found that shades the target-shade area at ground level at all times when the UV index has a value of 2.5 or above. For each specific site, a series of vectors can be constructed from a dense grid on the target-shade area to all critical solar positions. Figure 3a shows the vectors going from a selected number of critical solar positions to the target shade area (illustrated by a green square). The points that lie on these vectors and intersect a specified horizontal clearance plane, positioned parallel with the plane defined by the target-shade area, form a point cloud. The height of the horizontal clearance plane (typically in the order of 2.8 m to 5 m) permits activities beneath and around the shade to continue uninterrupted. The complete point cloud and the clearance plane are shown in Figure 3b. Although the point cloud is contained by an irregular form, it can be enclosed by a range of contour forms. The size of the plan area at clearance height is a function of the service-time period and the height of the horizontal clearance plane [56]. With the plan area at clearance height established through the shading analysis, a structural surface, which will include this point cloud contour, can be generated.

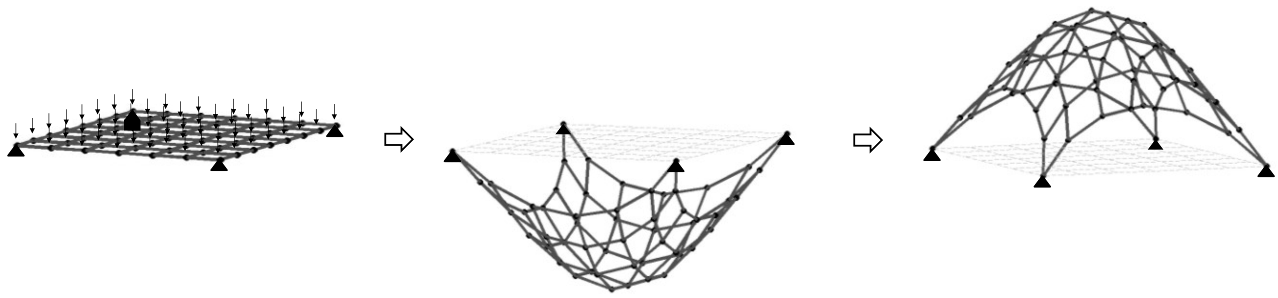
Figure 3. (**a**) Shading analysis establishes the critical solar positions for a dense grid on the target-shade area; (**b**) A contour encompasses the point cloud that lies at the intersection between the critical solar vectors and the plane at clearance height, positioned parallel to ground level.



4.1.2. Form Finding

A number of structural typologies (such as truss, space frame and arching systems) are available to span large distances without intermediate supports. In this context, a grid shell structure, a curved lattice-like framework, is favored as this rigid curved surface resists external loads most efficiently through membrane stresses. A grid shell is essentially a shell with its structure concentrated in a relatively fine grid of beams. The grid shell structure can reconcile the competitive design drivers of shading and structure in an integrated manner. By also assigning the grid shell beams the shading function, the shading elements become part of the structural system and are effectively integrated, multi-functional components. Using a numerical form-finding technique [50] based on a hanging particle spring model, the global geometry of the grid shell can be developed. This process requires an arbitrary starting geometry. Different starting geometries with different support conditions and element orientation will generate different form-found shapes. However, all form-found shapes have to encompass the plan area defined by the critical point cloud in order to function as effective built shade. In this paper, an initially rectangular geometry is chosen and simulated as a network of springs, supported at its four corners. The form-finding approach lets this network relax under gravity loads, applied at the spring connections (Figure 4a). As a result, a hanging form, consisting of a grid with tensioned springs, arises (Figure 4b). Upon freezing and inverting this form, a compression only grid shell geometry is achieved. Compression only systems are favored as they achieve structural efficiency (Figure 4c).

Figure 4. (**a**) Initial grid network of connected springs supported at its 4 corner extremities forms the initial geometry for the form finding process; (**b**) Upon application of loads at the spring connections, the grid relaxes into a tension only curved network; (**c**) When inverted, the form for a structurally efficient compression-only grid shell is generated.



(**a**) (**b**) (**c**)

4.1.3. Louver Orientation

Once the grid shell form has been defined, the characteristics of the shade-beam elements are examined. The louver depth and cross-sectional orientation of the shade-beam elements should create a continuous projection surface over the target-shade area for the area to be effectively shaded. The louver depth, initially oriented vertically along the form-found grid lines, is defined by structural and construction criteria. Although this system is structurally optimal, it does not satisfy the requirement of shading the target area of all critical solar positions; the solar radiation can still go through the apertures between the louvers onto the target-shade area. To guarantee that the point cloud contour is encompassed by the developed grid geometry and to identify the orientations of the louvers, an iterative procedure is set up for which the reader is referred to [56].

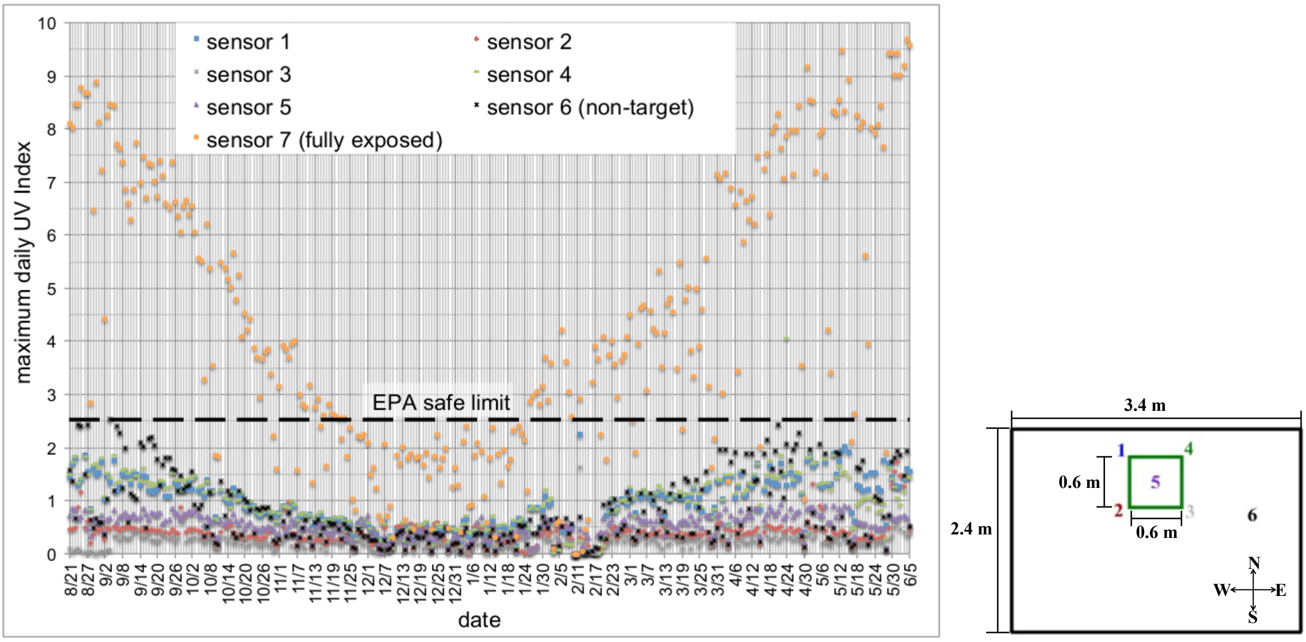
4.2. Experimental Validation of Solar Radiation Control

A small scale prototype of the louvered grid shell was designed, constructed from western red cedar wood and tested to shade an area of 0.6 m × 0.6 m in Princeton (NJ, USA, latitude 40.36 N). The grid shell, composed of a curved lattice of shade-beam elements, spanned an area of 2.4 m × 3.4 m and obeyed specific vertical clearance height (defined in Section 4.1) at the centers of the boundary arches. The shade-beam elements (19 mm × 184 mm) were oriented parallel with the East-West direction. Seven Davis sensors [57] in conjunction with a Campbell Scientific CR1000 data logger [58] measured the UV Index at five minute intervals for the time period August 21st 2013–June 5th 2014. Five sensors (numbered 1, 2, 3, 4 and 5) were located within the target shade area, while sensor 6 was located outside the target-shade area but still underneath the louvered shell. Sensor 7 sat on top of the shell and was exposed to the open outdoor environment. Figure 6 shows a sample of the data collected along with a plan view with the sensor locations. While the recorded UV indices atop the shell and on the ground outside the target shade area were occasionally in excess of the health hazard limit of 2.5, the indices recorded within and on the boundary of the target shade area did not reach those limits. Hence, the built shape of the structure provided appropriate shading protection validating the design methodology proposed. While the temperature under the prototype, with direct solar radiation being blocked, was usually lower than the outside temperature, there was enough natural light for outdoor activities to take place (Figure 5).

Figure 5. (**a**) South-West; (**b**) North-West elevation; (**c**) inside view of the louvered grid shell prototype built.

(**a**) (**b**) (**c**)

Figure 6. Maximum UV Index values recorded by the sensors (see plan view for sensor locations) located in (sensors 1–5) and outside the target area (sensors 6 and 7) for the period 21st August 2013–5th June 2014.

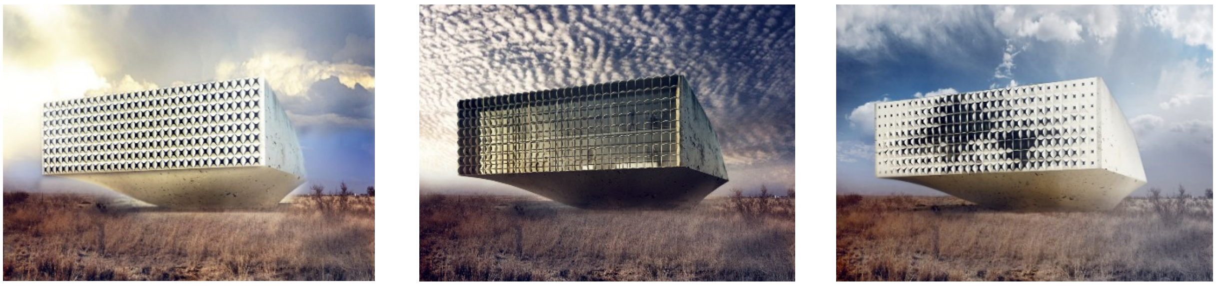


5. Application 2: A Dynamic Shell Shading Module for an Adaptive Building Façade

The design of an adaptive dynamic shading enclosure requires an approach that uses environmental performance, structure and kinetics as design drivers. Adaptive dynamic building enclosures must respond and adapt to multiple design variables such as weather, context and occupancy. The interactions among these variables are inherently dynamic, non-linear, stochastic and multi-dimensional. These features, in general, have led to the development of adaptive building skins, which already prove to have significant operational energy saving potential, by as much as 51% [59,60]. The logic of adaptive performance is compelling: it promotes reduced energy consumption and increased occupant comfort [61]. Although the performance of adaptive enclosures might depend upon the occupant's preferences, its efficacy meets or exceeds that of a fixed system. However, as discussed in Section 2, current dynamic adaptive building enclosures rely on a large series of mechanically complex hinges and costly actuation systems to adapt their shape. The shell module, presented in this section, challenges the promotion of such systems with kinematics based on elastic structural deformations. The proposed module shows that elastic deformation can be a successful shape-shifting strategy for lighter and mechanically less-complex dynamic adaptive façades.

Since the efficiency of a shading enclosure is three to five times higher when installed on the exterior of a façade compared to the inside installation [60], this section focuses on the design and engineering of a dynamic shading shell module for an exterior building façade. Figure 8 shows renderings of the presented adaptive dynamic shell module on the exterior façade of a south facing façade near Austin (TX, USA, latitude: 30.21N). The opacity of the façade can be varied in response to external and internal conditions. At noon, solar radiation control is required and the façade shows a small aperture to surface area ratio (Figure 7a). At twilight, the transparency of the façade is increased to allow for more solar radiation (Figure 7b). Depending upon the architectural program behind the façade, a varying degree of opacity might be desired during different seasons and at different times of the day (Figure 7c). The behavior of the adaptive dynamic shell module façade under wind loading is out of the scope of the paper. However, the proposed modules are shape-resistant structures that can potentially sustain wind loading in their open and closed configuration based on their strained state, module-to-module and system behavior.

Figure 7. Adaptive dynamic shading module mounted in the exterior façade of a museum in Texas (**a**) at noon, (**b**) at twilight, and (**c**) adapted for a varying architectural program behind the façade.

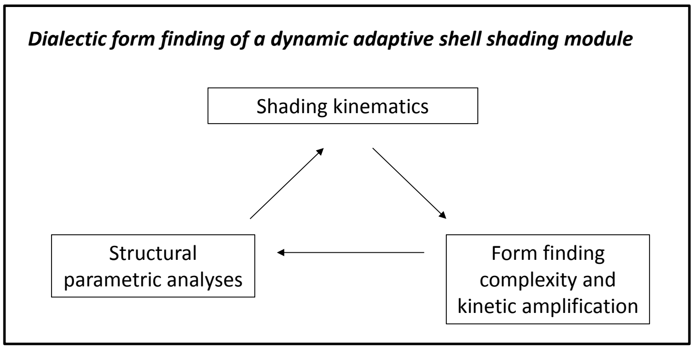


(**a**) (**b**) (**c**)

To design a high performance dynamic shading enclosure that is integrated, multifunctional and adaptive, while using minimal operational energy, two concepts are important: complexity and kinetic amplification. In a complex system, a small change in one part cascades down into the other parts and gives rise to a collective, emergent behavior of the entire shading system. In particular, in the context of a dynamic adaptive shading enclosure, a single degree of freedom motion in one component would give rise to an emergent motion of the entire shading module. To minimize operational energy, the applied actuation would also have to be small and result in a controlled shape transformation of the shading module over a wide range of opening or closing stages. This concept is termed *kinetic amplification* and results in an energy efficient kinetic system.

Figure 8 illustrates the dialectic form finding approach for the dynamic adaptive shell shading module. In this case, the process starts with the definition of the shading kinematics based on the desired solar radiation control (controllable shape changes that can be used to provide shading). Form-finding is then employed for the definition of an appropriate shape for the system. Among all solutions explored, solutions with high complexity and kinetic amplification are preferred. Structural analyses are then performed to inform how the structural behavior and the shading kinematics of the system can be improved.

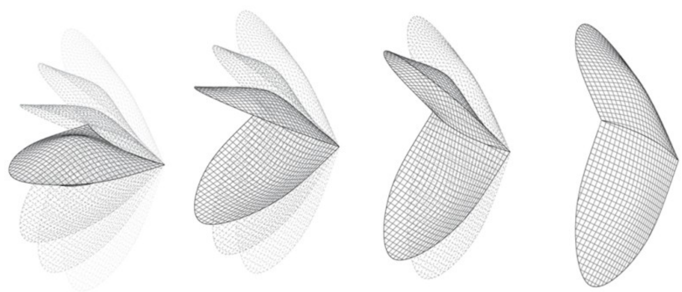
Figure 8. Illustration of the iterative integrated aspect of the dialectic form finding for the dynamic adaptive shell shading module.



5.1. Physical and Numerical Dialectic form Finding Bounded by Structural and Kinetic Criteria

The kinetics of the proposed shading module are shown in Figure 9 and consist of the controlled minimal bending of a central beam element (a single degree of freedom motion) with two attached flexible shells. When the central beam deforms the shells displace as a result, but do not deform. Designing dynamic adaptive systems is a complex task, as both the behavior during the shape transformation and when static in operation needs to be accounted for [62]. Therefore, in this paper, physical models and non-linear FE models [63] are employed. Physical models provide insight into the shape shifting and a proof of concept, while the FE models are employed to exactly describe the geometry as well as the structural and kinetic behavior of the system at all phases of the full scale shape-shifting process.

Figure 9. Through the controlled bending of the connecting beam element, the attached flexible shells demonstrate a large complex movement.



A physical model of the dynamic shading module was built and tested as proof of concept. The model is 20 cm tall and assembled from two 0.1 mm thick Polyethylene Terephthalate (PET) shells attached to a ASTM TM2 15 mm × 0.36 mm bimetallic beam. The bimetallic beam reacts to a temperature difference by bending with uniform curvature and, hence, provides the required actuation. The displacement δ on the middle of the beam is given by [64]:

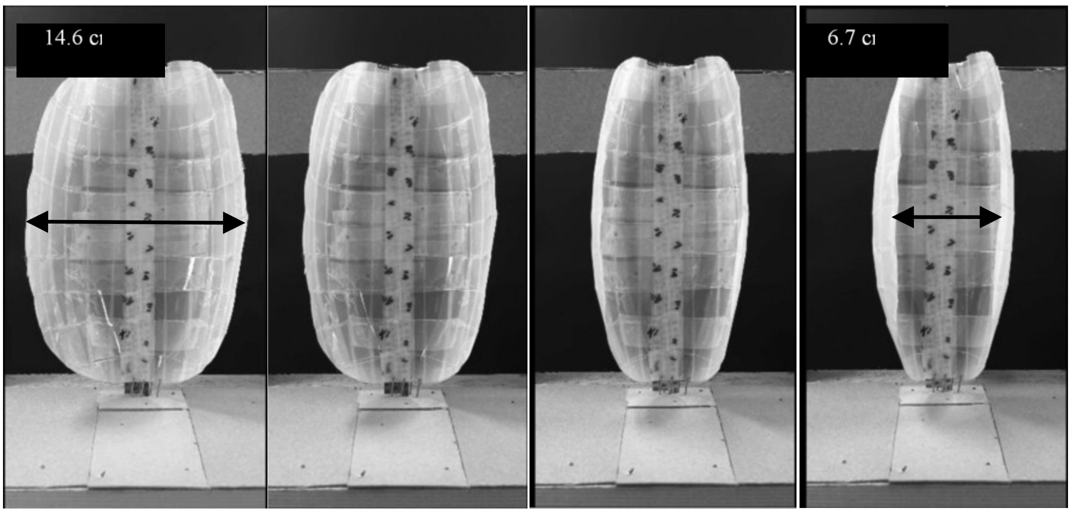
$$\delta = \left(\frac{l}{8R}\right)^2 \tag{1}$$

where:

$$\frac{1}{R} = \frac{6(\alpha_1 - \alpha_2)(T - T_0)\left(1 + \frac{t_2}{t_1}\right)^2}{t\left(3\left(1 + \frac{t_2}{t_1}\right)^2 + \left(1 + \frac{t_2 E_2}{t_1 E_1}\right)\left(\frac{{t_2}^2}{{t_1}^2} + \frac{1}{\frac{t_2 E_2}{t_1 E_1}}\right)\right)} \tag{2}$$

with l the length of the beam, R the uniform radius of curvature, α_i the thermal expansion coefficient (°C^{-1}) of layer i, t_i the thickness of layer i (m), t the thickness of the material (m), E_i the Young's modulus of layer i (N/m^2), T the current temperature (°C) and T_0 the initial temperature (°C). The deflection occurring in a 1m long bimetallic beam, made of standard ASTM TM2 material with Young modulus of 141,000 N/mm^2 and two 0.005 m thick layers, and with expansion coefficients of 23 × 10^{-6} °C^{-1} and 2 × 10^{-6} °C^{-1} under a temperature difference of 10 °C, is approximately 0.004 m. The bimetallic beam can thus be designed accordingly based on a required displacement or a given temperature difference. PET is chosen as material for the shells in this initial table top model, as its material properties combine strength and flexibility. Figure 10 shows different phases of the complex movement of the shading module.

Figure 10. Physical small scale prototype, before (**a**) during (**b**), (**c**) and after (**d**) a temperature increase is applied to the connecting beam provides insight into the geometric and mechanical relationships between the beam and shell components.

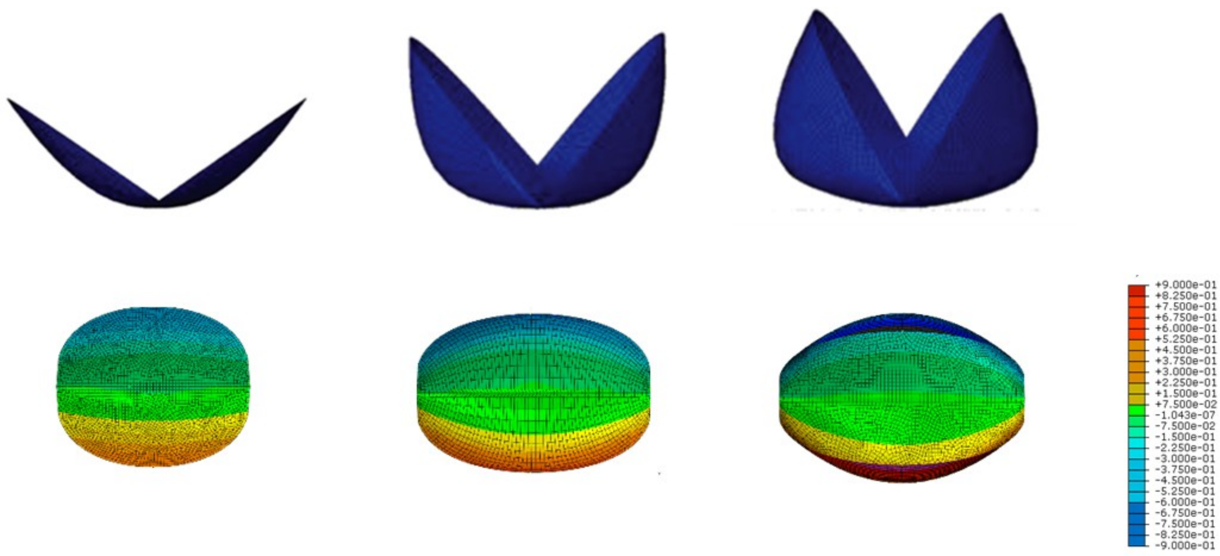


(**a**) (**b**) (**c**) (**d**)

When a uniform temperature increase is applied to the bimetallic beam, the beam bends and the attached shells close inwards. After approximately 10 s, the distance between the midpoints on the two free shell edges has been reduced by 54%. The small displacement of the bimetallic beam, in turn, triggers a larger displacement on the PET shells. The model confirms both the kinetic amplification and the complex movement in the proposed module. Furthermore, the model revealed that the bimetallic beam is the only component that deforms. The thin shells preserve their shape during the shape shifting, as they are out of the elastic deformation influence zone of the beam. The potential to scale and optimize the table top physical model to a dynamic adaptive shell module for an architectural building façade is explored using non-linear FE models.

When analyzed under static loads, FE models provide a better understanding of the stability, stiffness and strength of the shell shading module in its pure form and offer insight on how to balance elastic stiffness (set by material and section properties) and geometric stiffness (set by the system's form). The reference FE model is comprised of two different elements: 0.104 cm thick composite shells integrated into a pin-supported shallow upward-curved beam with a length of 3 m. When opened, the system's wingspan is 2.35 m, a dimension that provides coverage for a standard window size. Both shell and beam elements are made of a carbon/epoxy composite, which combines material strength and flexibility. The single degree of freedom actuation in the FE model is provided with a point load of 0.63 kN, applied perpendicular at the mid-span of the beam. Stresses in the reference model, under the applied external load, indicate that shell components primarily experience membrane action, in the direction parallel to the beam's longitudinal axis, and bending action in the other direction. In order to increase the kinetic amplification and thus have a wider range of opening and closing angles of the shells, the FE model is further used in a parametric study that explores the magnitude of the shell curvatures (Figure 11). The study demonstrates the important correlation between the shells' radius of curvature and the kinetic amplification.

Figure 11. Increasing curvature models and their corresponding displacements. The depth of the shell controls the curvature parameter with (**a**) depth 0.20 m; (**b**) depth 0.48 m; (**c**) depth 0.80 m.



(**a**) (**b**) (**c**)

5.2. Numerical Validation of Solar Radiation Control

The potential of the proposed form-found dynamic shading modules on reducing the cooling and heating loads of a building is investigated in this section. However, since adaptive elements are not supported by commercially available software, the effect of the dynamic adaptive shell shading modules was simulated by varying the window area in the building, while holding all other parameters constant. Therefore, simulations provide a theoretical upper bound estimation of the energy savings as they do not include aspects related to the module implementation such as the required actuation energy. Although the required actuation energy can be negligible when bimetallic elements are used, this is not the case for traditional mechanical actuators such as pistons.

In this study, the environmental performance of the building is evaluated using the commercially available software Ecotect [65] and EFEN [66]. The adaptive shell shading modules are assumed to be installed on the exterior of the curtain wall of a typical glass façade building in Princeton, NJ, USA. Preliminary analyses revealed that the implementation of the modules on the west and east façades had negligible impact on the cooling and heating loads. Therefore, the proposed modules are assumed to be installed only on the north and south façade of the building. The implementation of the modules on the façade is however out of the scope of this paper. In Ecotect, monthly cooling and heating loads were simulated for window areas corresponding to 100%, 66% and 33% of the original window area reflecting an opening angle in the module of approximately 90°, 70°, and 49°, respectively. For the same window areas, daily cooling and heating loads for every Thursday of the year were obtained using EFEN. The study revealed that installing the proposed dynamic adaptive shell shading modules can generate savings in annual cooling and heating loads between 14% and 43%.

6. Conclusions

Although the first air-conditioned building dates back to 1928, it was not until after the Second World War that mechanical systems were sufficiently developed to promote the environmental approach of completely separating the interior environment from its climatic and site context. However, with 21st century societal concerns of global warming and non-renewable resources depletion today, it is imperative to consider the building envelope as a climate filter that blocks, filters, accepts and rejects energy flows between the exterior and interior environment while creating architectural spaces that are healthy, pleasant and productive. Often though, the design approach still assumes that the building envelope is dictated by other parameters and that environmental and structural aspects can be resolved by detailing or making later modifications to a predetermined enclosure rather than with an integrated system approach such as dialectic form-finding.

The primary justification for the shading enclosure systems presented in this paper is passive and active solar radiation control through built form. The presented dialectic form-finding approaches resolve the conflicting design drivers of thermal performance, structure, and kinematics, in an integrated system using physical and numerical models.

The curved louvered lattice shell not only breaks down the barriers between internal and external space, but also between structure and climate filter. The beam elements in the grid shell become integrated oriented louvers that passively intercept UV radiation, only when harmful to human health and for a specific site location. The UV-index monitoring both underneath and on top of the louvered lattice shell prototype in Princeton, NJ, USA, showed that the structure provides yearlong protection from harmful UV radiation. Moreover, the proposed approach questions the established skin-cancer prevention strategies [67] which require structures with continuous surfaces such as solar sails and hard top roofs, disqualifying slat-roof systems (such as the louvered lattice shell) as potential candidates. This paper clearly shows that if (slat) lattice roofs are realized based on the dialectic form-finding approach, they mitigate the harmful effects of UV radiation efficiently, while promoting natural light and ventilation.

The dynamic shell shading module controls solar radiation in an active manner: it repeatedly and reversibly shift its shape to improve the environmental building performance. The structure and kinematics of the shading shell module are integrated in a complex system, where shape changes emerge from a multiplicity of simple interactions (*i.e.*, the bending of the connecting beam cascades down in the amplified closing movement of the connected shells). The proposed system can maintain a high performance level through shape control when operating conditions or functional requirements (such as architectural program) change in a predictable or unpredictable way. It can, thus, make transitions over time, meet new objectives and cope with uncertainty by exploiting the changes in its environment.

The process of dialectic form-finding could be extended beyond the development of solar radiation control enclosures and deal with trade-offs beyond shading, structure and actuation. Moreover, dialectic form-finding provides a holistic design approach that can be employed for multi-purpose hybrid structures that combine active and passive strategies. Finally, as the gamma of competing and conflicting design drivers expands (views versus privacy, daylight versus glare, fresh air versus draught risk, *etc.*), the introduction of numerical optimization techniques into the design process becomes desirable for generating a Pareto front of feasible design alternatives that resolve the dialogue between the different criteria.

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Author Contributions

Sigrid Adriaenssens developed the research plan, advised all tasks and wrote the paper. Landolf Rhode-Barbarigos co-advised all research. Axel Kilian consulted on the initial design strategy for the louvered grid shell and carried out a literature survey. Olivier Baverel advised the making of the physical models of the adaptive shading models. Victor Charpentier carried out the FE analysis of the adaptive shading modules and constructed the physical models. Matthew Horner developed the design methodology for the louvered shell, built and tested the physical prototype. Denisa Buzatu carried out the numerical environmental analysis of the building with adaptive façade modules. All authors proof read the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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