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Biography

Poul Henning Kirkegaard is MSc. in Civil Engineering from Aalborg University, Aalborg in 1988 and PhD in "Experimental Design" from Aalborg University, Department of Civil Engineering in 1991. Poul Henning Kirkegaard is today Full Professor at Department of Civil Engineering, Aalborg University in Innovative Design of Structures. His main research areas are related to Adaptive Structures, Computational Morphogenesis, Tectonic Form & Design and Evidence Based Design.

Development and Evaluation of a Responsive Building Envelope

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Abstract
Recently we have seen an increasing variety of applications of adaptive architectural structures for improvement of structural performance by recognizing changes in their environments and loads, adapting to meet goals, and using past events to improve future performance or maintain serviceability. The general scopes of this paper are to present the development and evaluation of a new adaptive kinetic architectural structure. This reconfigurable structure can transform body shape from planar geometries to hyper-surfaces using different control strategies, i.e. a transformation into more than one or two different shape alternatives. The adaptive structure is a proposal for a responsive building envelope which is an idea of a first level operational framework for present and future investigations towards performance based responsive architectures through a set of responsive typologies. A mock-up concept of a secondary environmental system to a primary structural system joint into a collective behavioural system equipment with an actuator system is presented.

1 INTRODUCTION

We have to face that recent years of impact of various environmental conditions, such as e.g. climate changes play an increasingly decisive role in the design of new architectural and civil engineering structures. Understanding the interrelation between these impacts and the built environment is of a major public and scientific interest. The increasing costs of energy, which are required for construction and maintaining buildings and structures require optimized structural solutions and the building envelope between the inside and outside environment becomes more relevant, in order to control the flow of heat, light, noise, information and other media. Although these impacts are not static most artificial products are static and they do not have the ability to react to changes in their environment. However, the time has come to make adaptive architecture which can adapt their performance, in real time, to environmental changes and use less energy, offer more occupant comfort, and feature better overall space efficiency than static buildings do. Adaptive architecture follows a trend which is emerging in *responsive architecture* coined by Nicholas Negroponte when he proposed that architecture may benefit from the integration of computing power into built spaces and structures, and that better performing, more rational buildings would be the result [1-3].
The introduction of adaptive systems into architectural engineering projects allows a new approach to form finding. Apart from traditional concepts, such as “form follows function” or “form follows force” the amount of energy brought into the system can influence the optimum geometry of the structural system: “form follows energy”. To build higher or to reach bigger span widths imply a need to use new techniques and new materials. New structures should be lighter in weight, consume less energy in construction and operation, and achieve higher performance levels than existing structures. The question is if structures could become lighter if they react actively to these effects from the environment in an adaptive manner, these structures have the potential of becoming self-optimising systems, based on smart strategies and smart calculation models. This could theoretically be buildings consisting of rods and strings which would bend in response to wind, distributing the load in much the same way as a tree. It may also become possible to devise adaptive architectural structures that can sense and respond to changes in their environments and ultimately providing better performance e.g. to changing external climate factors, such as win, rain, sun etc In general adaptive structures (smart structures) are sensing and reacting to their environments in both predictable and

unpredictable manners based upon the interrelations with structural and social influences, through the integration of various elements, such as sensors, actuators, power sources, signal processors, and communications networks. For a further development of adaptive kinetic architectural structures there is a need for solving e.g. the shape control based on inverse dynamics analysis of a multi-body flexible system integrated into an smart architectural envelope that seek fresh relationships between 'building' and 'user'.
The present paper presents preliminary results related to the development of a responsive building envelope and the holistic design incorporating structural and environmental design parameters will be discussed. The responsive building envelope is an idea of a first level operational framework for present and future investigations towards performance based responsive architecture.

2 Building Envelope Aspects

Research and technological innovation, during the last decade, have facilitated a major improvement in the performance of specific building elements like the building envelope - including walls, roofs and fenestration components - and building equipment - such as heating, ventilation, cooling equipment and lighting. Still most building elements still offer some opportunities for efficiency improvements, however, the greatest future potential seems to lie with technologies that promote the integration of "dynamic" building elements with building services. In this perspective the term "dynamic" translates into the fact that functions, features and thermo-physical behaviour of such building components may change over the time and adapt to different building/occupants requirements (heating/cooling, higher/lower ventilation, …) and to different boundary conditions (meteorological, internal heat/pollution loads, …) [4, 5]
This type of dynamic architecture follows a trend which is emerging in *responsive architecture* coined by Nicholas Negroponte when he proposed that architecture may benefit from the integration of computing power into built spaces and structures, and that better performing, more rational buildings would be the result [6-7]. This kind of interactive spaces are built upon the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of human and environmental interaction. Deployable, foldable, expandable and reconfigurable kinetic structures can provide a change in the geometric morphology of the envelope by contributing to making it adaptable to e.g. changing external climate factors, in order to improve the indoor climate performance of the building. Structural solutions for kinetic structures have to consider in parallel both the *ways* and *means* for kinetic operability. The *ways* in which a kinetic structural solution performs may include among others, folding, sliding, expanding, and transforming in both size and shape. *The means* by which a kinetic structural solution performs may be, among others, pneumatic, chemical, magnetic, natural or mechanical [6].
Kinetic structures can also be classified according to their structural system. In doing so, four main groups can be distinguished: spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, strut-cable (tensegrity) structures and membrane structures [7, 8]. Much research has been done with respect to improve the efficiency of these kinetic structural systems which can facilitate a flexibility in building design and give rise to a search for responsive architecture which can physically convert themselves to adapt to the ever-changing requirements and conditions. This could theoretically be buildings consisting of rods and strings which would bend in response to wind, distributing the load in much the same way as a tree. Similarly, windows would respond to light, opening and closing to provide the best lighting and heating conditions inside the building.

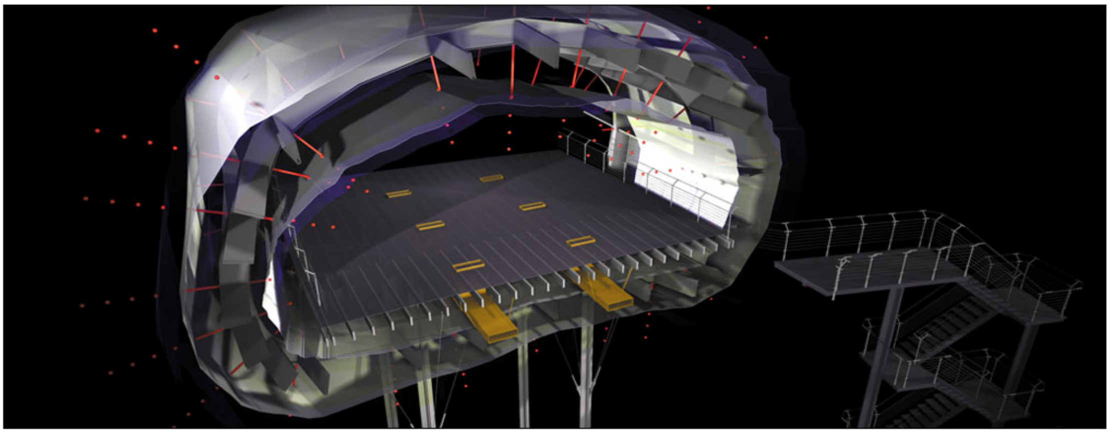

Figure 1: A responsive architectural space [9].

Tristan d'Estree Sterk of The Bureau for Responsive Architecture and Robert Skelton of UCSD in San Diego have been working on shape-changing "building envelopes" using "actuated tensegrity" structures, i.e. a system of rods and wires manipulated by pneumatic "muscles" that serve as the building's skeleton, forming the framework of all its walls [9]. Within the projects sensor/computer/actuator technologies are used to produce a series of intelligent building envelopes that seek fresh relationships between 'building' and 'user'. These responsive buildings are covered by skins that have the ability to alter their shape as the social and environmental conditions of the spaces within and around each building change, see figure 1. New, more personalized relationships with space will inspire fresh interpretations of architecture. Finally relationships that emerge from the juxtaposition of experimental performance and responsive architecture could lead architects to new sets of ideas that uncover new possibilities within architecture as well as provide performance artists with spontaneous, unanticipated, and serendipitous moments that further artistic expression.

3.0 TYPOLOGIES IN RESPONSIVE ARCHITECTURE

Dynamic systems in architecture are receiving a growing interest from researchers likely to be the result of accessible technology and inspirations from dynamic systems in nature and the surrounding environment. The unfolding potential of such systems reveal many intriguing questions related to architectures perception of *being,* all the way to designing and assembling explicitly defined multi-rotational robust joints.
Listed investigation areas thus frame a larger spectrum of specific research areas into one towards performance based responsive systems in architecture.

1. *Material Systems*
   The development of physical kinetic systems or the like are often developed within structural and mechanical engineering and material sciences.
2. *Informational Systems*
   The development of physical sensor systems, which to an increasing level can observe and send continuous information further to a processing system, which then actuate into behaviours passing information back to the environment.
3. *Processing Systems*
   The development of physical processing systems, which filter and decide from large amounts of sensor information and stored information. These are often associated and developed within computational sciences.
4. *Behavioural Systems*
   The development of logic and behavioural gestures, patterns and systems, often associated with artificial intelligence sciences based upon computational and neurological sciences.

To evolve an adaptable architecture, we work with all these areas of investigation. The material system is directly related to the physical presence, form, tactility and expression. Informational systems let us decide what dynamic information we will feed our architecture with. Processing systems let us decide in what way we handle the information and behavioural systems let us transform all this into an architecture that responds to many criteria's simultaneously. Some predicted, some unpredicted. In nature, responsive behaviour, is a common part of surviving and to evolve, based upon the possibility to catch food, as known from the Venus Flytrap [10] or to the optimisation of spreading pollen as seen in many flowers [11] . Such response is commonly one-directional and with a singular objective. In architecture, we face multiple objectives, such as structural dynamics, climatic dynamics and social dynamics. To construct adaptable architectural systems, we thus search more physical flexible systems and operational open systems, which can be informed by multiple sensors and multiple performance intentions. Based upon above areas of investigation a taxonomy of responsive and potential adaptable typologies can be described. While behaviours can be reformulated and 'inserted' into a physical processing system, as part of a physical material system it is very difficult at present state to rapidly adjust or completely alter a material system into something else than original intended. The material system constructed thereby boundary conditions for any applied behavioural intents. The taxonomy serves in this way also as a way to investigate into potentials and application for a specific typology based upon its properties. The current taxonomy, fully described outside this paper, is thus organised firstly from the material systems organisation, then processing systems and informational system. The designer adds behavioural systems outside any classification.

1. *Direct Response System*
2. *In-Direct Local Response System*
3. *In-Direct Global Response System*
4. *In-Direct Combined Response System*
    4a. In-Direct Discrete Response System
    4b. In-Direct Hierarchical Response System
    4c. In-Direct Coupled Response System
    4d. In-Direct Coupled Heuristic Response System
5. *In-Direct Holistic Response System*
6. *Direct Integral Response System*
7. *Direct Reconfigurable Response System*

Typology 4 has branches, as it is combines two or more responsive systems into one. How they are linked in their processing systems, informational systems and eventually behavioural systems is defined by their categorisations.

4.0 ENVIRONEMENTAL RESPONSIVE ENVELOPE

Here research based upon development of an *In-Direct Combined Response System*. Two or more systems are combined to form flexible operations and higher levels of morphological agility. The material system is divided into a primary structural system created upon inverse kinematic dynamics, enabling double curvature formations from an aggregated series of tetrahedral elements. A secondary surface system is applied to the primary, functioning as an open and closure system to control energy flow and visibility through the building envelope, see figures 2-5.


Figure 2: Model-back

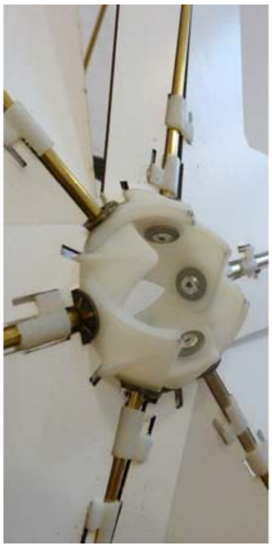
Figure 3: Joint

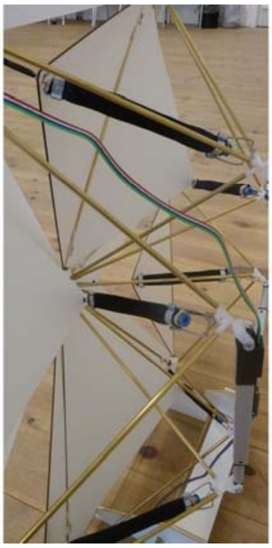
Figure 4: Muscle


Figure 5: Model-front

Temperature, light and sound sensors and processing units (microcontrollers) for the secondary system are locally situated to control a cluster of six open/closure mechanisms, with the ability to filter into control of each mechanism if intended. A separate processing unit (computer) is linked to the linear actuators for the primary structure, to be able to solve the more complex organisation of the inverse kinematic dynamics. Input to the primary system is delivered from the sensors locally situated and from stored information.

4.1 In-Direct Combined Response System

A processing configuration as described above enables two variations of the *In-Direct Combined Response System*, being an *In-Direct Discrete Response System* and an *In-Direct Hierarchical Response System*. While the first operates in a way where the two systems do not 'know' of each other, the latter is linked logically through the same sensor inputs, making it possible to construct hierarchical operations between the two systems. Behavioural operations are registered real-time through a series of response strategies described in the code, which can be altered from user input (programmer), stored data (memory) or changing sensor input (environment).

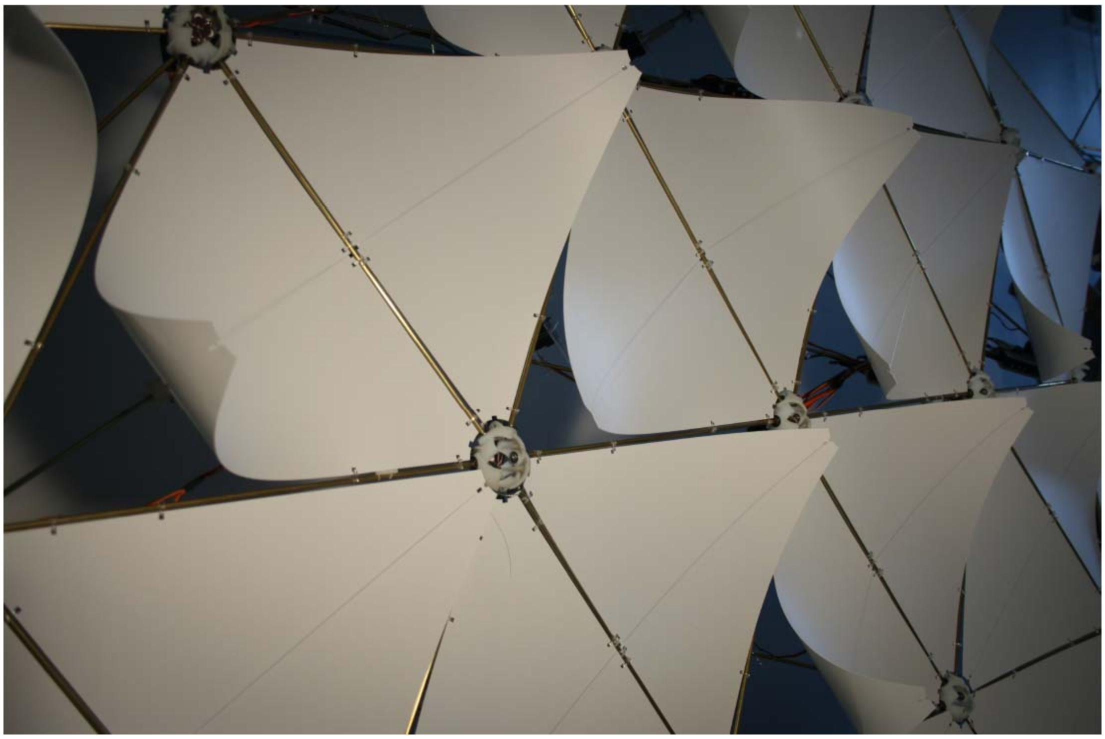

Figure 6. In-Direct Hierarchical Response Prototype of the front with actuated secondary system.

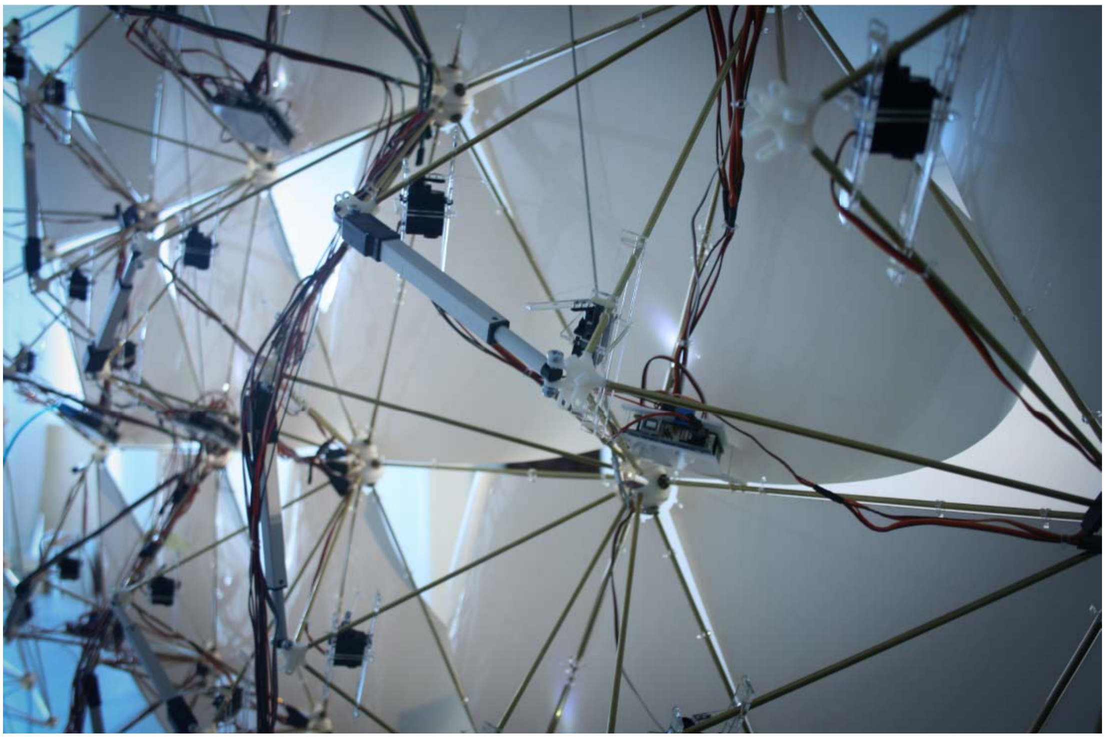

Figure 7. In-Direct Hierarchical Response Prototype of back illustrating the tetrahedral primary system with processing microcontrollers, linear and rotational actuators.

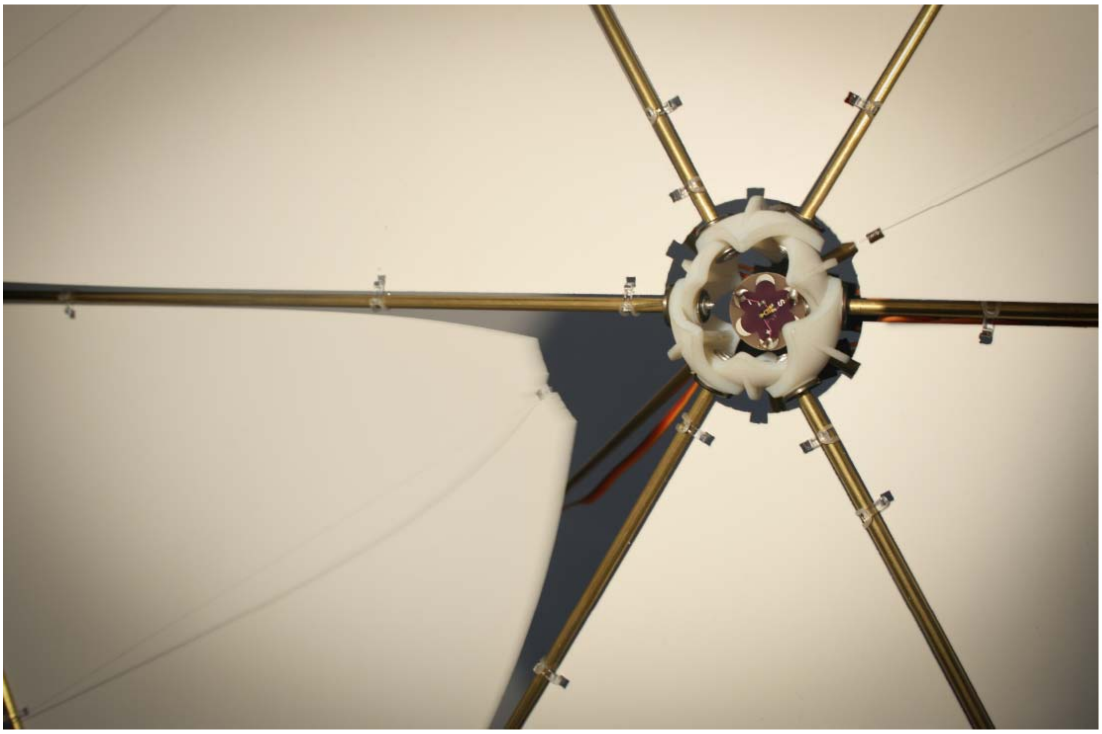

Figure 8. In-Direct Hierarchical Response Prototype details showing the rotational complexity of physical parts to enable the dynamics of the model, while maintaining structural stiffness.

Both systems might share code intent, like attempting to solve similar problems of reducing solar energy to pass through the envelope, but results in uncoordinated actions, as they do not search for a joint or coupled solution. This, however, has shown to create a very understandable and immediate response to altering climatic conditions.

5.0 Environmental Responsive Performance Envelope

In moving the two combined systems into a state of performance, they are parametrically modelled, figure 9 and simulated within digital climatic analysis environments for solar exposure, light transmission and thermodynamic flows, see figure10. Various formations of the complete model illustrate the properties of the system as a dynamic envelope, responding to continuous alterations. This data has been used to create response strategies, as a first generation response [12]. A later, more refined response will be present as the system learns from the environment and the behaviour of its inhabitants.

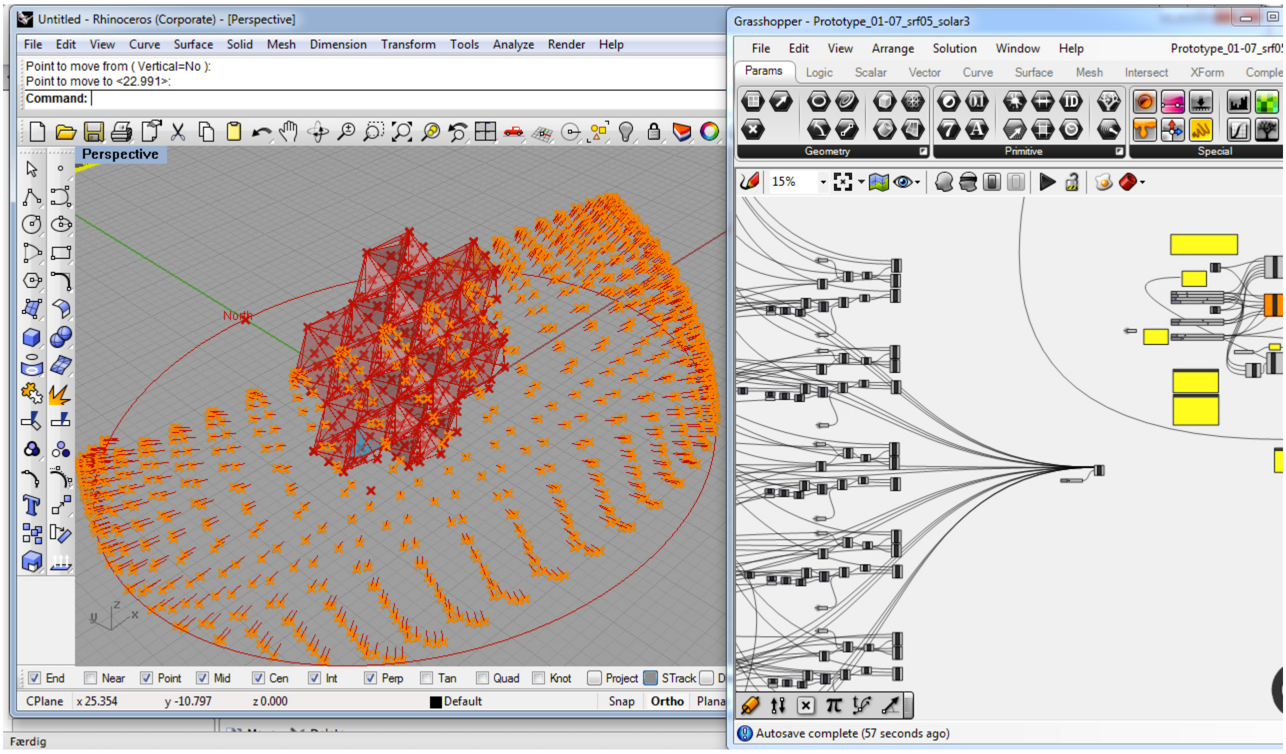

Figure 9. Digital parametric model including the primary and secondary systems able to perform dynamic adaptations to environmental data.

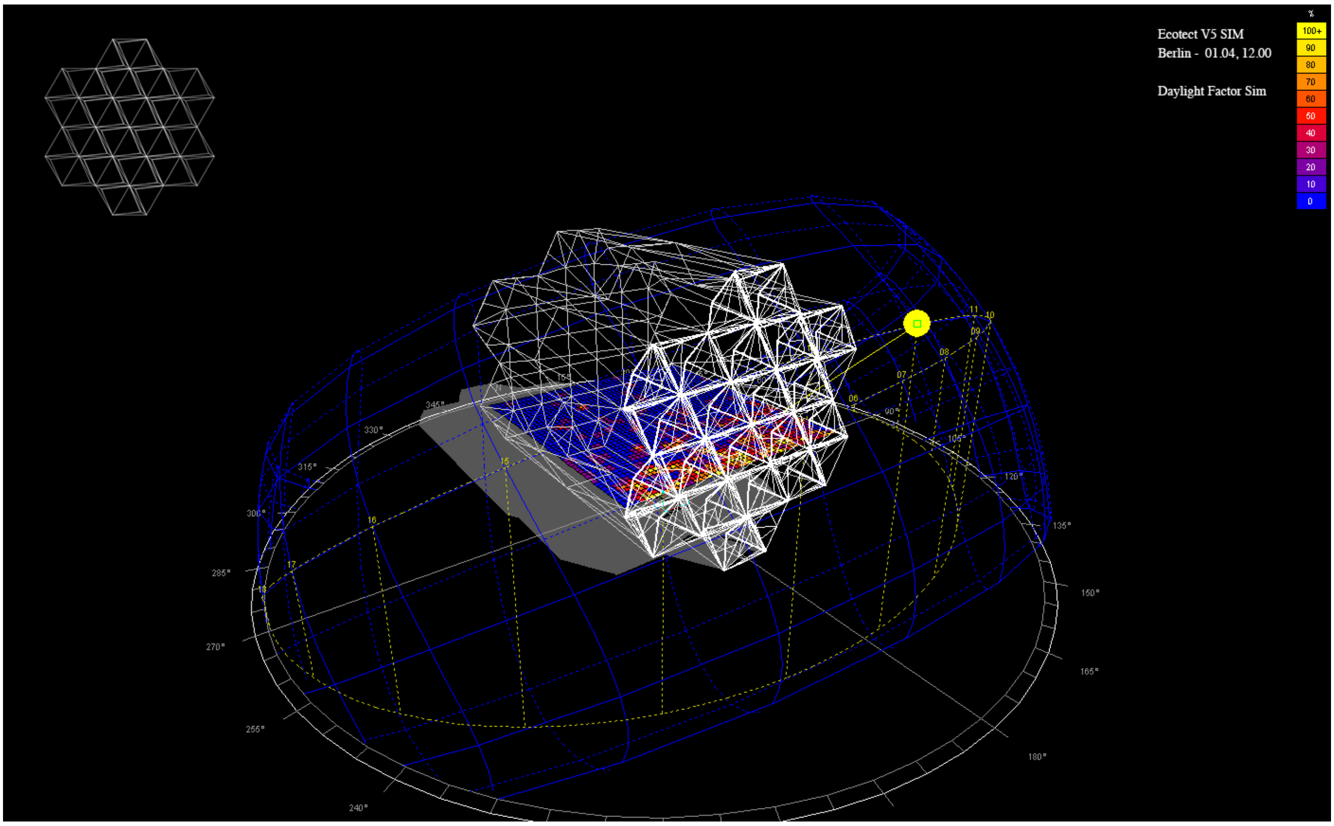

Figure 10. Environmental simulations analysing radiation and solar transmission through the envelope model.

6.0 Conclusions

The operational framework, based upon deductive reasoning of existing work, enables a series of typologies, which again fosters concrete investigations into future responsive systems, customised to different approaches and needs. A first level prototype has been developed and exploited by the 'Performance Based Design Lab' at Aalborg University through the '*In-Direct Combined Response System*' prototype, enabling adaptive transformations upon multi-objective criteria. Performance is in this research related to both the quantitative measurements of climatic environments through the applied sensors as a consequence of the responsive envelope behaviours and equally the qualitatively creation of architectural effects of shade and light patterns, atmosphere from changing perceptual enclosures and the tactility and emotional effects of the structures. The work emphasise on multi-objective solution finding, with focus on structural, environmental and social dynamics to reach sustainable and lasting systems to future architectural implementation. In this respect the presented work serves as a step towards *In-Direct Coupled Response Systems*, which are expected to improve energy use, directly through minimisation of energy usage within the processing system by optimising information flow and by harvesting energy from both external sources as well as the energy released via the physical kinematic dynamics. Affected environments from the dynamic formations are equally expected to improve indoor spaces by continuously searching an optimised comfort according to occupancy and known architectural strategies such as night cooling, cross ventilation and surface solar exposure. Improvements can be created through the discrete systems working collaboratively, to which future research work will focus on large prototypes within hierarchical and coupled responsive typologies to advance operational performance of the models. The research opens to more investigations based upon the merge of architectural and engineering aspects into performance based responsive building envelopes.

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