LONG-TERM ADAPTATION

in

Climate Adaptive Building Shells

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10 January 2013

MSc Thesis

Eindhoven University of Technology
Long-term Adaptation in Climate Adaptive Building Shells

Design & Performance Assessment

10 January 2013

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LONG-TERM ADAPTATION IN CLIMATE ADAPTIVE BUILDING SHELLS: DESIGN AND PERFORMANCE ASSESSMENT

Abstract

Contrary to the traditional philosophy which considers buildings as static systems with fixed properties, climate adaptive building shells (CABS) introduce performance possibilities through the adaptation of their properties in response to changing ambient meteorological conditions and occupants’ requirements. The timescale of adaptation can range from seconds to years, following weather time resolutions. This paper explores, besides CABS potential benefits, the involved attributes and impacts of several design variables on the performance of building shells which adapt throughout monthly or seasonal epochs (time base). By applying building performance simulation (BPS) and bi-objective optimization, we manage to lighten the interpretation of the outcome of monthly sensitivity analysis (SA) so as to identify the important design variables through CABS lifecycle and then we propose a specific framework for reducing their complexity. Employing an office zone case study, we demonstrate how Pareto front combinations allow the assessment of CABS optimum potential over different number of epochs. Furthermore, the actual capabilities that monthly SA has in defining which of the design variables are worth considered fixed or adaptive through CABS lifetime are emphasized. This paper concludes with the observation that further attention and research over the proper accommodation of the balance between CABS complexity and performance degradation is imperative in order a definitive assessment of the efficiency and opportunities of long-term adaptation in buildings to be feasible.

Keywords: climate adaptive building shells, long-term adaptation, epochs, complexity, sensitivity analysis, fixed/adaptive variable

1 Introduction

The worldwide claim for reforms in all aspects of modern human life towards a development which meets present needs without compromising those of future generations has been converted
into an intense demand. In compliance with it, the integration of higher levels of sustainability into the building sector has become prominent. Nonetheless, it was only the last few decades that the building design priorities were assembled into the necessity for low-energy buildings that offer a satisfying indoor environmental quality at the same time. Meeting this challenge is manageable as long as building shells, which are located at the boundary between inside and outside, act as climate mediators negotiating between comfort needs and the ambient environment.

However, building design society traditionally endorses strategies which consider building envelopes as “static” systems, aiming passive robustness as an answer to varying operating conditions. This approach entails the clever determination of designs that remain high value perceived across changing environments and preferences. The result is highly opaque insulated constructions which besides the apparent energy saving benefits, do not efficiently deal with the challenge of satisfying energy and comfort requirements simultaneously. They remain insensitive to various changes and they are unable to capture all the potential energy and comfort possibilities that the varying weather conditions can offer. Therefore, even when their design is an outcome of optimization process, such static buildings perform as a good compromise over their lifecycle in dynamic changing conditions. The amplitude of environments along with the inability of robustness to deal with differences between system’s offering and user’s expectations challenged designers to come up with new, innovative building components, in an effort to integrate flexibility into buildings’ design (Ross et al., 2008).

In this concept, Climate Adaptive Building Shells present an interesting approach regarding the way buildings interact in dynamic environments, since they can actively adapt their behavior in response to meteorological changes and occupants’ variable comfort needs. The sensible and effective implementation of this notion generates remarkable opportunities, both for energy and comfort gains and enables building envelopes to act as climate mediators between indoor requirements and ambient conditions. Existing literature offers several terms to describe this design approach so this paper is based on the following definition (Loonen 2010): A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variably boundary conditions, and does this with the aim of improving building performance.

The idea of system adaptability is not recent and like many concepts in engineering domain, was inspired from behaviors and trends in the most dynamic environment of all, nature. Likewise birds abort their old feathers preparing for the winter and bears fall into hibernation in order to endure severe winter conditions, humans also adjust their rituals by changing clothing or replacing their cars’ tires from winter to summer. All the above behaviors derive exactly from the same urgency; meeting their new requirements. Loonen (2010) tried to translate it into the buildings domain by defining the four critical elements that compose CABS adaptive attitude.
One of the most interesting aspects of this behavior is related to the timescale with which they change the values of their design variables. Depending on the change resolution of the weather phenomenon they target, it can range from seconds to years. While short-term adaptation is mainly connected with short time resolutions (i.e. seconds, hours, diurnal) observed in natural patterns (e.g. wind speed change, sun movement, etc…), long-term adaptation pertains to gradual boundary weather condition alterations, generally recognized through months or seasons.

No matter the time range of analysis chosen, it is undeniable that the exploration of a dynamic changing system over time is a profound task that frequently requires the aid of computational resources for an integrated approach. The advent of several building simulation (BPS) tools and more efficient optimization algorithms, has enriched the decision making process with means enabling considerations at a pre-design level and problem analysis at a higher level of details than the traditional ones.

Besides the apparent opportunities that computational methods offer, the deployment of BPS and optimization strategies in CABS exploration and assessment is presently unclear and their benefits have not been fully exploited yet. There is an adequate number of studies that use computational techniques to describe the optimum nature of various building components (e.g. fenestration, shading systems) under different performance objectives and constraints (Manzan and Pinto, 2009; Wright and Mourshed, 2009; Ochoa et al., 2012). Their conclusions, though meant to promote robustness, achieve to reveal the promising impact that the embracement of adaptivity in the integration of these optimum designs would exert on shells’ performance.

However, CABS literature itself, fails to demonstrate a higher level, holistic design approach of such visionary buildings and the structural role of BPS against design ambiguities, presented in the very early stages of such innovative process, has not yet gained acknowledgement. At present, it is confined mainly to specific case studies which try to evaluate, with the aid of simulation, the adaptive behavior of individual building components, such as shading devices (Reinhart, 2004), smart windows (Trcka et al., 2011) and dynamic insulation (Burdajewicz et al., 2011).

Since the attributes, interactions or even involvement of the design parameters in the performance of CABS are apparently yet unexplored; only assumptions regarding the potential benefits of CABS can be done and building society is deprived of crucial information, regarding the research directions that are worth being investigated.

The first attempt for an integrated macroscopic approach of CABS, under the light of BPS, highlights a series of directions that needs scientific address and introduces the arising opportunities of their proper application in the context of the two above-mentioned timescales (Loonen et al., 2011). Despite its importance, this study intentionally remains in an abstract level.
willing to open the discussion around CABS and not elaborate deeply into a specific type of adaptation. So, further research on the potential and better understanding over the engagement of BPS and optimization, in the analysis of both short-term and long-term adaptive character of these shells, are needed.

Short-term adaptation presents intuitively as more opportune in performance, since it enables more frequent responses to natural elements, enlarging the possibility for potential performance benefits. However, the apparent associated cost of the introduced (system) complexity in the building envelope should be reflectively considered. Changeability every minute or hour, though appealing, requires more sophisticated technology, additional mechanisms mounted on façade level and careful control strategy and attention on the continuous components co-ordination. Since the whole concept of CABS is yet not mature and the progress in the field is characterized by fragmented developments, long-term adaptation arises as an alternative, obviously worth exploring, which can offer conceivable performance profits over building shells lifetime with less challenging and likely less expensive technological applications. Thus, CABS integration and expansion appear faster and closer to reality, hopefully adding valuable information and insight for the more challenging case of short-term adaptation.

This paper is not meant to give specific, straightforward design instructions over the actual application of CABS concepts in particular type of buildings, contexts or climates. It remains on a higher level of proposing and exploring strategies that may prove stimulating for different interested parties, from actual building designers and product component developers up to energy policy makers. Therefore, through a specific case study and always under the notion of long-term adaptation, this paper will try to (i) assess the performance potential of CABS, (ii) specify their design features through detecting which and how characteristic façade’s design variables influence their performance, and (iii) discern the factors that primarily contribute to building shell’s complexity and afterwards quantify their impact.

The ultimate goal of this scientific work is to explore the possibilities of reducing CABS complexity without soundly disturbing performance, increase understanding and enable design recommendations, if possible, towards the enrichment, upgrade or even reforming of the climate adaptive building shells philosophy.

After presenting the binding conceptual intermediary for analyzing the problem in a proper perspective, this paper describes all the necessary steps followed to explore and construct the core outcome of this research; the general workflow proposed for handling CABS complexity properly and efficiently. It concludes with the application of this workflow in a specific office zone and the discussion of the involved restrictions and possible challenges for future research.
2 Research Frame

2.1 Conceptual Background

The study of a building that changes its design over time and the analysis of the involved dynamic processes related to its complex behavior is quite an uncharted procedure. Hence, in an effort to accomplish them, the deployment of other developed, though untested in buildings area, strategies appears quite reasonable. The absence of a conceptual framework, that will enable us to evaluate the value delivery of a building under changing contexts and the progression of time, activated a broader inquiry in systems engineering field. As a result, we decided to make use of an approach inspired by epoch-era analysis (EEA); a system design strategy developed by Ross and Rhodes (2008), already used in order to assess the functioning of flexible space engineering systems over their mission’s duration (Fitzgerald & Ross, 2012).

As far as buildings are concerned, epoch, the base unit of EEA, represents a period of time characterized by a static set of variables and operational conditions which are expected to change into certain bounds. Era, in this case, is considered as the entire lifetime of a building. Through specifying eras which comprise of ordered sequences of carefully defined epochs, we create the necessary foundation on which BPS and optimization strategies will be performed in a structured way. For the purposes of time effect evaluation, the epoch duration throughout this paper varies from one month (base unit defined by Gregorian calendar) till the period of a year. Regarding a specific climate selection, weather variance from year to year is not taken into consideration, so the same weather data information for every year of simulation are used, thus confining the era of the building under examination to one year. Therefore, in this paper, epoch duration of one year is just denotative, representing the traditional static building shell.

As far as computational techniques are concerned, multi-objective optimization (MOO) appears critical since building design inherently requires the continuous accommodation of existing trade-offs between two or more conflicting design objectives (e.g. energy vs. comfort). The main advantage of this approach is that trade-offs are represented as a set of equally optimum solutions, the Pareto front, from which a single design is selected according to the decision-maker priorities.

A traditional method for multi-objective optimization is the weighted-sum method which reduces a MOO problem into a scalar one and provides a single solution point that reflects preferences incorporated in the selection of a single set of weights. However, such an approach leads to single objective problems which deprives us from one of the core intentions of this research; the effect exploration of design variables through visualizing the involved objective trade-offs. Additionally, this method would require adjusting the weights of the objectives from month to month since the preferences in buildings change over the year and thus it would increase the
computational complexity. For these reasons, the deployment of such a strategy was judged unfavorable to our goals and it was not chosen.

Furthermore, charting the impact that different design variables have on the performance objectives demands the engagement of an alternative approach which enables the provision of information beyond the level of simply defining the Pareto optimal front. According to the influence that design variables have on the position of solutions relative to the optimal trade-off in multi-objective problems, they are divided into two main categories (Huband et al., 2006):

- **Distance variables** (noted as “d” in Figure 1) define solution trends into the optimization cloud and their values determine how close to the Pareto front a solution lies.

- **Position variables** (noted as “p” in Figure 1) define solution trends along the Pareto front and their values determine where a solution lies along the Pareto curve. No patterns are matched to the behavior of these variables through the cloud.

![Figure 1](image)

**Figure 1:** The effects of position (p) and distance (d) variables on the Pareto front (dashed line) in a bi-objective optimization problem.

While this categorization sets the base for a more high level analysis of optimization solutions, existing literature moves one step further by extending and enriching these definitions (Brownlee & Wright, 2012) into:
• **Primary** and **secondary position variables**, based on whether a single dominating trend is exhibited along the whole Pareto front or periodic fragmented trends influenced by another variable can be distinguished respectively.

• **Floating variables**, which exhibit no solution trend either in the optimization cloud or along the Pareto front, indicating that objective functions are hardly sensitive to them.

• **Hybrid variables**, whose behavior is a mixture of all the above mentioned attributes.

These definitions offer an important toolkit in our effort to decipher the long-term dynamics of CABS. They can increase our understanding about how design variables can affect shell’s performance and strengthen decision making process towards informed design decisions.

### 2.2 Problem Description

As determined in the introduction, this paper will identify the contribution of building design in the struggle for balancing between **complexity** and **performance**, the two conflicting objectives governing CABS entire entity. Next, after setting the framework around these goals, the addressed problem is defined.

**Complexity**

CABS are typical examples of complex systems and this feature expands from the level of their actual implementation to the complexity of the interrelations between elements embodied in their operation. While the development and manufacturing of adaptive building components pre-requisites innovative design technologies, the allocation and advanced control of the additional mechanisms mounted on façade level further add to the system’s complication. In essence, there is nothing wrong with complexity since it is inherently interconnected to smart technologies; however, our principle endorses less complicated systems.

This paper aims to address CABS complexity from a higher point of view, focusing on defining the operational and conceptual design characteristics of their adaptive behavior while letting the feasibility issues and the construction/production details of the associated building components out of the scope of this work.

In this context, the complexity will be examined as a function of the number of epochs deployed and the number of the design variables under investigation that are worth being adaptive (change their physical values) through the building’s lifetime. It is natural that, in comparison to
conventional static shells, design complexity augments as the number of epochs and adaptive design variables increase.

**Performance**

The performance of CABS, just like other buildings, is described by a set of objectives which translate design strategies and decisions into specific goals. Due to the innovative aspects of this concept, performance should be defined by carefully selected objectives and indicators in order to explore the important details and concerns involved in such a design process.

**Problem Definition**

The problem that this paper addresses, originates from the fact that the number of possible combinations in the complexity area is very large:

- The existence of \( \alpha \) (not zero) design variables under investigation creates \( \left[ \frac{\alpha-1}{6} \times \alpha \times (\alpha + 1) \right] + \alpha \) possible combinations regarding the number of adaptive variables
- An annual era can consist of 1 to 12 epochs creating 298 possible epoch combinations (in the previous relation setting \( \alpha=12 \))
- The final sum of possible cases for examination is: \( 298 \times \left[ \frac{\alpha-1}{6} \times \alpha \times (\alpha + 1) \right] \)

Considering that the number of possible steps in the value range of the design variables was not taken into account above, it is not only difficult but also incompatible with the high level perspective of this paper to investigate and quantify the CABS performance for all these cases, one by one, in order to address the relationship between complexity and performance.

So, in compliance with the statements in the introduction, the goal of this research paper is dual; besides gaining insight over the performance benefits that long-term adaptation can introduce in buildings, we are challenged to explore and define, if existing, the conditions (or the path) with which a significant decrease in the CABS complexity can be accompanied with the least possible loss in adaptive shell’s overall (expected) performance improvement.
All the above can be condensed into the following research questions:

1. What are the potential benefits from the integration of monthly-seasonal adaptation in the building envelopes and which approaches are appropriate for demonstrating the optimum performance of such adaptive building shells?

2. How can we facilitate a process for identifying which main design variables of a building shell are worth to be considered fixed and which adaptive, in the concept of long-term adaptation (refining number of adaptive variables)? What is the optimum (or near-optimum) frequency of adaptation (refining number of epochs deployed) and at which point of shell’s lifetime (defining time point of transition between epochs)?

3. What is the impact of the above selection on the building performance and how does it accommodate the involved constraints and trade-offs towards an efficient transition of CABS into reality?
3 Methodology

In order to accomplish the goals of the project and to examine the long-term adaptation aspects of a building shell, a series of actions and steps are followed. Below, the phases from which our methodology is composed are described while on later stages of this paper, the application of this process in a specific case study will be presented.

3.1 Case Definition

Although the timescale of adaptation is already pre-decided throughout the whole paper, this phase consists of a series of important arrangements that will facilitate the creation of a realistic case study, enabling us to address the goals set in the beginning of this work. Besides the accommodation of the type of building used and the corresponding climate, this stage mainly concerns the definition of shell’s design and performance. First, the group of design and physical parameters and their value ranges that will be investigated, should be carefully chosen. Pre-design considerations about their realistic nature, their significance for a building’s performance and their suitability for an adaptive concept, should guide the selection.

Performance should be described through its educated division into clear and well-defined objectives. Therefore, the deployment of the appropriate performance indicators (PI) will allow the conduction of a sensible and meaningful evaluation of CABS efficacy.

3.2 Analysis Tools

After the considered model set-up is completed, BPS tools are employed in order to quantify and analyze the shell’s performance. Supplementary, sensitivity analysis and multi-objective optimization techniques can contribute insight and information towards a comprehensive methodology for the accommodation between CABS complexity and performance.

3.2.1 Sensitivity Analysis (SA)

SA process integrates the method used in Monte Carlo Analysis (MCA) and is divided into three partitions: a) pre-processing, b) simulation and c) post processing. First, all input parameters are sampled for generating a reasonably accurate random distribution. The simulation phase is
executed using software simulation tools that are able to evaluate the energy and daylight performance of dynamic systems such as buildings. Since the minimum length of possible epochs is the monthly period and we originally want to decipher the effects of time on yearly performance, monthly sensitivity runs, instead of the traditional annual ones, are employed.

Post-processing constitutes the bone of SA and regression analysis is selected since it offers quantitative measures of sensitivity. Pearson coefficients, a type of standardized regression coefficients (SRC), are selected and the whole output analysis is achieved using one of the several available appropriate computational environments for data analysis. More information about the justification over the selection of the specific SA tools can be found in Appendix A1.

### 3.2.2 Multi-Objective Optimization (MOO)

In this paper, bi-objective MOO is applied and the treatment of more than two objective functions which leads to a three-dimension Pareto surface is left for future work. Monthly optimization iterations of building shell’s performance are executed and the examination of its optimal behavior and (design) attributes are divided into monthly intervals. Hence, the assessment of building performance, both over a complete year (static case) and over twelve individual monthly epochs (adaptive case), becomes feasible.

### 3.2.3 Outcome Analysis & Next Steps Decisions

The available data from the two above-mentioned phases are apprehended, evaluated and significant decisions for further computational actions are made.

The regression analysis during the SA serves two critical missions: (i) getting an initial insight over which of the examined parameters, all varying at the same time, exhibit a substantial impact on the objectives, and (ii) eliciting a set of possible epoch combinations for the next steps of computations. Consecutively, MOO enables monthly observations regarding the attitude of input variables within the (Pareto) front and the cloud of the objective space. Concurrently, input’s impact is assessed and is matched with the attributes described in Section 2.1.

Based on the information and insight gained from these two processes, further optimization cycles, involving a refined number of input parameters and epochs, are executed for achieving the goals of this research work.
4 Results – Proposed Strategies

Building design process is significant for the lifetime performance of a building, so decisions should be made under deliberate consideration in order to prevent, as many inefficient choices, as possible. Whereas the appearance of advanced BPS and optimization tools has facilitated pre-design decisions, the complexity of design variables’ interrelations along with the adaptation that CABS espouse, probably convert this pre-design stage, a demanding, work loaded and time consuming task.

In order to deal with this difficulty, a two-stage strategy is developed and proposed. In the beginning, we administer a higher level of significance to sensitivity analysis that enables the elicitation of richer and more valuable knowledge out of it. This phase is one of the key foundations of this research and indicates how standardized regression coefficients can interpret and reveal such information that would normally be available after MOO.

The second phase utilizes the generated outcome and consists of a specific, straightforward sequence of steps in order to reduce complexity and simplify the implementation of long-term adaptation in CABS. Through these steps, the proposed methodology introduces a systematic and quick way to define the proper number of epochs that preserve value delivery, in comparison to a fully adaptive building, and evaluate those variables that are worth considered as adaptive.

4.1 Define key variables for CABS using SA

Section 2.1 introduced and prioritized the identification of the effect that input parameters have on selected objectives as a central point in the attempt to explore the performance of CABS through monthly adaptation. However, this operation prerequisites the execution and observation of optimization iterations, which can be highly time consuming in the concept of CABS.

In this paper, we give examples how the behavior of the input variables in the objective space of optimization is linked to the extent of their Pearson correlation coefficient. Additionally, we propose the following relations between PEAR coefficients and the attitude of a variable, in the case of a design problem with two conflicting (positive/negative coefficient) objectives.
Table 1: Identifying design variable’s significance using sensitivity analysis techniques.

As far as the above relations are concerned, in case of non-conflicting SRC, all the variables behave as distance, except from the floating ones which keep the same character.

Finally, it needs to be mentioned that the above categorization over the correlation strength, incorporates a reasonable level of resilience when the edges separating the different classes are considered. This is helpful in order misinterpretations and false decisions to be prevented.
4.2 Framework: Defining Epochs characteristics & Fixed/Adaptive variables

The notional bridge required for exploring the resolution of CABS complexity was developed in the previous section and gives us the ability to present the following framework in compliance with the research goal of this paper.

**Step 1.** Execute Sensitivity Analysis for each month, using regression coefficients analysis

**Step 2.** Identify the primary position variable(s) according to Section’s 4.1 mapping

**Step 3.** Determine the number, length and transition points of the selected epochs

**Step 4.** Identify the role of the other variables through the selected epochs

**Roles**

a. *Floating* variables through all the selected epochs are worth treated as static (fixed) and the selection of their values is insignificant to the building’s performance

b. *Distance* variables through all the selected epochs are worth treated as static and the selection of their values is significant to the performance of the building. The edge (min or max) of the range of each variable is chosen depending on the sign of the correlation

c. *Primary position* variables through all the selected epochs are worth treated as adaptive and their values through them are determined through MOO process, since they highly influence the building performance

d. *Secondary position* variables through all the selected epochs are worth treated as adaptive and their values through them, is determined through MOO process, since they influence (less than primary) the building performance

e. *Different combinations* along the epochs are possible and correspond to adaptive variables with their values through these epochs to be determined, according to their role (*distance, position*) in each epoch. In the special occasion that these values, from epoch to epoch, coincide (either due to optimality or to decision–making processes), then the variable degenerates/behaves as static during the lifetime of the building
5 Demonstration Example of CABS Performance Potential & Proposed Framework Application: CABS office zone

After introducing all the necessary information over the nature of the case study, this example is divided into two contextual parts. In the first part, the CABS performance potential is explored while afterwards, the implementation of the methodology proposed against CABS complexity takes place. Results out of a multi-objective optimization analysis are used to establish a solid ground and verify the information extracted from the regression sensitivity analysis executed. Finally, the outcome of the application of the involved steps is extensively discussed.

5.1 Description

5.1.1 Building Model Characteristics

This example analyzes the behavior of a single-person south facing perimeter office zone (3.6m x 5.4m x 2.7m), situated at an intermediate floor and surrounded by identical office zones. The building, which is evaluated under Dutch climate, employs no mechanical cooling system (free running) and is only occupied during office hours. Ventilation system utilizes outside air temperatures to renew inside air. The external façade wall consists of one layer (0.35m thickness) and its properties are determined by optimization. The upper and lower bounds for its design parameters are given in Table 2.

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<th>Parameter</th>
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<td>Density</td>
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<td>Thermal capacity</td>
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<tr>
<td>Thermal conductivity</td>
<td>0.1 – 2.5</td>
</tr>
<tr>
<td>External surface absorptance</td>
<td>0.1 – 0.9</td>
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<tr>
<td>Window to wall ratio (WWR)</td>
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<td>Glazing ID</td>
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Table 2: Overview and range of design variables.

Table 3 shows the detailed properties of the glazing types that correspond to the above mentioned IDs. Our interest will be directed on the influence of the glazing resistance only.
<table>
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<th>Glazing ID</th>
<th>Type</th>
<th>Design</th>
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<td>0.18</td>
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<td>4/16/4</td>
<td>0.35</td>
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<td>3</td>
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<td>0.71</td>
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<tr>
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<td>4/16/4</td>
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<td>0.622</td>
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<td>4/16/4</td>
<td>0.79</td>
<td>0.591</td>
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<td>6</td>
<td>Insulating, Ar, 1.3</td>
<td>4/16/4</td>
<td>0.79</td>
<td>0.624</td>
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<td>7</td>
<td>Insulating, Kr, 1.1</td>
<td>4/16/4</td>
<td>1.16</td>
<td>0.598</td>
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</table>

*Table 3*: Overview of the available glazing properties.

We focus on addressing two of the several fundamental necessities of each building shell, energy demand and thermal comfort. In line with the holistic approach of the CABS performance, visual comfort is not neglected, although not an objective itself. External blind system is “ideally” controlled on the basis of the active users profile. This stochastic algorithm assumes that blinds settings are rearranged on a regular basis with the aim of maximizing daylight availability while preventing direct sunlight on the workplane (Reinhart, 2004). Artificial lighting (10 W /m² installed power capacity) is switched on/off only when daylight availability is not sufficient to retain illuminance of 500 lx on the workplane, which in this example, is placed 1.45 m from the external wall. Thus, visual comfort requirement is, indirectly, taken into account through the blinds and lighting operation.

The energy saving potential of the adaptive shell is assessed by considering the primary energy demand of the zone which is divided into the energy required for heating and artificial lighting electricity.

Among the available indices that have been developed to express the feeling of thermal comfort, we deploy the adaptive thermal comfort (ATC) approach. However, as a supportive tool for argumentation reasons over ATC behavior, once, the simpler index of overheating (over 25 °C) hours is also used. ATC approach links the indoor operative temperature with the outdoor (running mean) air temperature, through the prediction of the “neutral or comfort” temperature (Nicol and Hamphreys, 2010). It is meant only for naturally conditioned spaces, as the office investigated, and it presents specific advantages over the classical comfort indices; therefore it appears appropriate for moderate climates, like in the Netherlands (Linden et al., 2008).

Thermal conditions in the zone are controlled on the basis of indoor air temperature, with the set point adjusted always 2.5 °C lower than the neutral temperature (known *a priori* for specific weather data used) from 7 a.m to 17 a.m and to 17 °C when the office is unoccupied.
5.1.2 Simulation and optimization methodology

Building performance simulations were conducted using TRNSYS tool (TRNSYS, 2011) in which daylight data were coupled from independent dynamic daylight simulations in the same zone, using DAYSIM (DAYSIM, 2011). For sensitivity regression analysis, all design parameters were sampled 150 times using a Latin Hypercube Sampling (LHS) method since it can deliver solid results under such a restrained number of samples (Hopfe, 2009). The actual SA output data analysis along with the necessary MOO cycles were executed using modeFRONTIER; a commercial, multi-objective design and optimization environment (Esteco, 2011). Optimization process was conducted using the non-dominated sorting genetic algorithm II (NSGA-II).

The objectives that should be minimized are:

i. The sum of the heating and artificial lighting (primary) energy demand [kJ]
ii. The number of hours per year that $|T_{diff}| > 3$ K, where $T_{diff}$ is the temperature difference between the indoor operative temperature ($T_{op}$) and the comfort/neutral ($T_{conf}$) temperature (Category II in Standard EN 15251)

5.2 Results

5.2.1 CABS Performance Potential via Monthly Optimization Combinations

Figure 2 shows the annual performance results for two types of building shell, the static and the monthly adapting (12 epochs). In this graph, each (grey cloud) dot represents a single building design for the examined static building shell and the Pareto optimal designs out of this group of available solutions, is indicated with black. We observe a quite sparse cloud and thus a rather quick convergence towards optimal solutions. An interesting point derives from the fact that the front for the traditional office zone is quite steep indicating relatively weak conflict effects between objectives and thus tempting design team to take decisions almost only towards better indoor environment. However, this shape of the front curve may be ascribed to the nature and realistic character of the thermal comfort index (ATC) that we apply (Nicol and Hamphreys, 2010). The repetition of exactly the same optimization with a simpler and less realistic (thus less favorable for the specific office zone) thermal comfort index, such as the number of overheating hours over 25 °C, leads to a smoother trade-off curve (magenta line).
Figure 2: Comparison of Pareto sets for monthly adaptive CABS (12 monthly epochs) and static building design shell. The Pareto front of the same static building shell using overheating hours (over 25 °C) as thermal comfort indicator, is also presented (magenta line).

In the concept of long-term adaptation, one of the clearly defined goals of this paper was to reveal the performance opportunities that CABS offer through the comparison of the performance between a static shell and a fully adaptive, over yearly basis. Therefore, dividing the year into the maximum number of epochs, we get the generation of twelve (monthly) Pareto fronts out of these twelve optimization periods. The fronts for each month along with their optimization clouds can be found in the Appendix A2.

By making all the possible combinations out of these fronts, optimal CABS design options are created on year-round basis. The outcome is also a cloud of solutions, like the one for the static zone, and its corresponding Pareto front can be seen in Figure 2 in red. It is readily remarked that the observation over the curve’s steepness, is even more striking in the CABS occasion. This complies to our expectations because in comparison with the corresponding (static shell) Pareto front (black curve), months are disconnected with each other, optimized separately and afterwards combined on annual basis. Therefore, the higher steepness is quite expected. Besides this argument, there is also an explanation which derives from observations in the Pareto fronts of the twelve epochs. During the winter months (epochs), when obviously heating consumption is intensive, Pareto fronts are single points (single objective optimization) and discomfort is almost non-existent. Consecutively, through the rest (non-winter) epochs when actually energy demand and discomfort are conflicting, the substantially lower magnitude of energy (heating) demand then, leads to a steeper curve on yearly basis, as shown in Figure 2.

Initially, if evaluated under the concept of energy demand reduction, the application of CABS on monthly adaptation basis, does not seem quite promising. For example, if the design team
accepts a discomfort range of 238 hours per year (89 % comfort level) for both cases, then the abatement in energy consumption is around 18 per cent on top of the best performing static design (points A and A’). This percentage is quite small when taking the added level of complexity of such a fully adaptive office shell inserts, into account.

However, the possible potential of long-term adaptivity in building shells is revealed when evaluating the above plots under the thermal comfort (and visual indirectly) perspective. The fact that CABS office zone offers the opportunity of achieving a highly superior indoor environment (theoretically zero discomfort hours, point C) and still have energy savings around 15 % (in comparison with the best performing static design, point A’) is notably significant. Although the effects of indoor environmental quality on productivity have become recently an issue of investigation, there is already lot of research work pointing towards the positive relationship between a good comfort indoor environment and the employees productivity in office spaces (Kosonen and Tan, 2004; Leyten et al., 2012). Therefore, the benefits from a possible application of this innovative concept can be much more substantial than those reflected on a single energy reduction percentage.

Albeit the disclosure of the performance aspects and opportunities associated with the implementation of CABS is properly addressed with the use of the above scatter plots, it is also interesting to give an insight over the design space of this optimum (red curve) fully adaptive office zone. Because the number of possible design options and variables is great, Figure 3 demonstrates the optimum value progression of window to wall ratio (WWR) and (external wall) conductivity for three representative curve points, a compromising middle point A (238 hrs), the one with the maximum (point B) and the minimum discomfort level (point C). The fixed value of the best performing static design point A’ is indicated with the dashed line.

**Figure 3:** Design values of two variables for three indicative design options of CABS office zone. The dashed line represents the value for the best compromising point of the static building shell.
The remark done previously over the steepness of the CABS Pareto front can now be visualized; during the winter epochs (1, 2, 11 & 12) all three points have the same values for the examined variables. This is the result of the MOO front being degenerated into single point due to the lack of conflict. In addition, it is not peculiar that different design points can have different adaptation frequency for the same variable (e.g. conductivity adapts three times per year for the point A while six for the point with maximum discomfort, B). As we will see next, the frequency of adaptation is independent of the impact that the variable has on the objectives and indicates no significant information over whether it should continue being treated as adaptive or fixed.

While conventional building shells incorporate a static restricting design in order to compensate for their several performance requirements during the year, CABS offer the opportunity of design freedom towards a better result. For example, based on Figure 3, instead of being constrained to buildings with relatively small windows (30 % WWR) all year long, occupants living in CABS get the chance for varying their window’s size, experiencing the same indoor environmental quality with higher visual flexibility.

5.2.2 Framework Application

While the first part of the results was devoted to the arrangement of the first research question of this work, we will now implement the workflow of section 4.2; one of the fundamental foundations of this paper which was developed for handling with the goals presented in the remaining two research questions. Based on this office zone example, the steps of the proposed framework are going to be demonstrated and analyzed in order its involved strengths and weaknesses to be properly addressed.

**Step 1 & 2: Sensitivity Analysis & Design Space Exploration**

Besides the demonstration of the first two steps, the scope of this part is to enlighten and strengthen the content of information that can be elicited from a simple regression sensitivity analysis. In this manner, a path towards the final stages which will help us accomplish our ultimate goal, the complexity reduction of CABS, can be created. Next, we will link SRC coefficients with insight regularly requiring time consuming optimization processes and we will solidify, even upgrade, the mapping presented in Section 4.1.
In Figure 4, the monthly (Pearson) correlation of the design variables, under investigation, is depicted in the context of sensitivity analysis. The correlations for the design variables, density and capacity, are omitted (found in Appendix A3) since their coefficients for all the months are slightly above or below zero. The impact on each of the objectives is denoted with a different colored column while the (coefficient) value ranges from -1 to 1. For enabling a practical reflection on the data presented in Table 1, the boundaries for interesting correlation values are denoted with colored dashed lines.

From the tornado plots above, a first insight over which and how variables affect the case study objectives, is available. It is clear that when all variables are changing values simultaneously, energy and discomfort are actually insensitive to the capacity and density of the external office layer (wall) since correlations are nearly zero during all the months (see Appendix A3). External
absorptance of the façade behaves in almost the same manner. On the other hand, WWR exhibits the strongest impact on both objectives, especially during spring-summer months and it allocates this leading role to the thermal conductivity and glazing resistance for the rest of the months.

According to the guidelines presented in Section 4.1, capacity, density and absorptance, for nearly all the months, behave like floating variables since they exert negligible influence on both the objectives. WWR appears to get the primary role during the non-winter months and thus act like the triggering force for the observed trade-offs. Hence it is justified, according to the definitions given in Section 2.1, to be characterized as primary position variable. The fact that discomfort is not present through the winter months, along with the substantial impact that conductivity and glazing resistance have on the energy demand objective enables us to assume that they exert a dominating role in direction of the cloud of possible design solutions; behave so as distance variables. Finally these parameters continue sustaining a considerable role during the spring-summer months but it is obvious that the level of their effect on the observed conflicts, is masked from the dominating character of the window to wall ratio variable; so probably they act as secondary position variables.

The validity of the above notions would be questionable unless there is enough information, from actual monthly optimizations which will support and enrich these initial assertions. Therefore, analysis of the existing trends for different months within the cloud of available solutions and observation on the Pareto fronts of the optimum designs is crucial.

Figure 5 shows the results of optimization, for months April and August. On the vertical axis is the discomfort hours number depicted while on the horizontal, the energy demand for the office zone. With black, the Pareto optimum solutions are denoted. The purpose of this months’ selection is done for demonstrative reasons in order to explore whether the investigated variables are behaving in the way we expect, based on the regression sensitivity analysis. The same analysis is possible for all the months.

**Figure 5:** Scatter plots of all the available design solutions and fronts out of optimization process conducted for April (left) and August (right).
In Figure 6, we can see how conductivity and capacity influence the position of design solutions in the optimization cloud, during April. To facilitate the analysis, the value range of each variable is matched to a color map, so as every possible design solution (bubble) in the objective space to get its color according to the value of the input parameter under observation.

As far as conductivity is concerned, we notice that design solutions converge to a specific tint of the color map, as they are approaching the Pareto front; the distance attitude of this parameter is expressed. Regarding the behavior of conductivity along the front itself (see Appendix A4), the fact that a variable behaves dominating in the cloud does not entail a specific attitude on the corresponding Pareto front. In other words, a distance parameter can behave as fixed (e.g. October), secondary (e.g. September) or even floating (e.g. April) on the front curve. These plots can be found in Appendix A4. On the contrary, capacity, as expected, does not exhibit any specific trend either in the solution space or even on the Pareto front (slightly noticed also in this figure), verifying its floating character.

![Figure 6: Bubble plots of all the available design solutions colored based on their values of conductivity (left) and capacity (right) for April.](image)

We employ the same strategy of color mapping in order to reveal the tendency of other three variables, window area (the same as WWR since south wall area is known, 9.72 m²), glazing resistance and conductivity during August; in this occasion, the trends on the front itself are under investigation. The only difference with the analysis before is that the size of the bubbles is determined by the underlying value of the window area, while the color information remains the same as denoted in April analysis above. In this way, possible dependence of a secondary position variable from a primary one will be exposed.
The window area (i.e. WWR) exhibits a straight inclination along the front curve, since the size of the window area determines on which position a design option is located. Solutions with bigger windows will be on the top of the curve presenting less energy demand (as indicated also by the negative correlation, in SA of Figure 4), while the smaller one will lie on the bottom part of it. The influence of this primary position parameter is visible not only on the objectives but also on the behavior of conductivity and glazing resistance. As the window area is changing along the front, local trends, indicating that better insulation and glazing resistance favor lower energy consumptions, can be distinguished. They are recognized in Figure 7 as clusters of bubbles with different diameter.

The involvement of observations into the objective space, using optimization techniques, was imperative in our effort to enforce the credibility of the information that can be derived from the early stages of a design process; the sensitivity analysis. Therefore, the bridge needed towards the attainment of a framework for reducing the complexity of CABS adapting in the long term is present and its last steps are analyzed in the following sections.
Step 3: *Epochs Selection*

The sensitivity analysis points towards the window area as the *primary position* variable of the CABS office, so we focus our attention there for identifying the epoch’s characteristics. However, it should be noticed, that this epoch identification process is not exclusively based on one group of variables but the whole trends and patterns present in all the variables’ coefficients are taken into account. Next, we start the implementation by tackling the number and transition point of epochs first and afterwards we enrich the refinement with decisions over which and how many variables are treated as adaptive.

As seen in Figure 4, from April till August, the impact of WWR on both the objectives is remarkably strong, signaling towards the consideration of each month separately as an epoch. However, as far as the number of epochs is concerned, the scope of this research is to explore the possibilities of complexity reconciliation through drastically reducing the adaptation frequency and thus reaching the seasonal time resolution. In compliance with this principle, we can consider these months as one epoch since the extent of the correlations for both objectives is quite similar, and secondarily, pick September and October as another epoch with less influence. Further, we witness that for the remaining months, conductivity and glazing resistance take over the dominating role and exhibit the same behavior. Façade with high insulation value and windows with thermally superior glazing are the main characteristics needed for an optimum performance during these months. Therefore, we can treat these months as another epoch.

We divide now, according to the above reasoning, the year period into three intervals, generating three new Pareto fronts out of these three optimization periods. By making again, as in the case of the fully adaptive office, all the possible combinations out of these fronts, the optimal performance of the office adapting three times per year is added next to the Pareto fronts of Figure 2, with the green color.
Figure 8: Comparison of Pareto sets for fully adaptive CABS (12 monthly epochs), seasonal adaptive (3 epochs) and static office design shell.

As mentioned in the beginning of this case study, the potential benefits of seasonal adaptation are not clearly revealed by denoting the fact that only 8 per cent energy savings is accomplished, in case that comfort level of 89 per cent (238 discomfort hours) is accepted. The motivation and its advantages are acknowledged when it is figured out that with the energy consumption of the best performing static design, a comfort level of 97 per cent is achievable in the seasonal adaptive shell.

Step 4: Design variables role determination through epochs (fixed/adaptive)

It is essential at this point, to examine all the prospects for further complexity degradation, focusing on the role of the design variables through the selected epochs. WWR is the only primary position variable in two out of the three epochs, so it is going to be treated as adaptive and its value will be the outcome of optimization and design decision processes.

As discussed in step 3, if the value choice for conductivity and glazing was based only on the first (winter) epoch, picking the edges of their range would be a prudent decision. However, the fact that for the rest two epochs, they behave as secondary position variables leads us to consider them also adaptive. Finally, there are three variables (absorptance, capacity, density) which act as floating ones during the selected adaptation periods. Hence, they will be approached as fixed
parameters and since their value choice is insignificant to the office performance, their central range value is used.

The only particularity, which imposes a design limitation in this case study, is related to the numerical method that TRNSYS tool employs to solve the differential equations used for thermal flow calculation. Certain combinations of the variables which define the external wall (conductivity, density and capacity) are not permitted. Their mixture consequences to extremely low values for the diffusivity (measure of wall’s thermal inertia) and the execution of thermal calculations is prohibited. Because of the significance of the conductivity as variable, we are forced to choose a low density value (400 kg/m³) instead of the central one, so as all the values in the range of conductivity to be eligible.

It is interesting to apply these decisions, not only in the three epoch office but also in the fully adaptive one, in order to evaluate the shell’s performance. Therefore, we follow exactly the same procedure as in the previous occasions.

Additionally, in an effort to move one step forward, we decide to treat glazing resistance as fixed for the epochs when it behaves as secondary and assign it the highest possible resistance. This decision is based both on observations out of the monthly optimizations and on the nature of this design parameter. Common practice shows that glazing resistance is always desirable in building design since it exhibits positive influence surely on heating consumption while it does not significantly harm indoor environment at the same time. Besides this argument, the secondary trends this parameter presents on the monthly fronts are not widespread along its whole range but they are confined towards high resistances (if not, the maximum possible).

Figure 9 incorporates all the new optimal fronts which are produced by applying the above mentioned decisions.
**Figure 9**: Comparison of Pareto sets for the fully adaptive CABS (12 monthly epochs), seasonal adaptive (3 epochs) and the static office shell. The fronts when only (i) two and (ii) three out of the six design variables are considered adaptive are displayed for the cases of three and twelve epochs respectively.

The decisions taken above seem effective and towards the right direction since they decreased CABS complexity, through reducing the number of adaptive variables to three, and they also did not significantly affect the performance of the zone. Specifically, for the case of twelve epochs, the maximum observed divergence (from 6 adaptive variables case) is in the area of 3.5 per cent (for zero discomfort) while for the case of three epochs is around 2 per cent (for 46 hours discomfort).

Additionally, the accommodation of glazing resistance as static variable proves out sensible since for both the adaptive building shells, the Pareto fronts nearly coincide with the corresponding fronts from the three adaptive variables office zone (divergences in the area of 1 per cent).
6 Discussion

This study is the first that attempts to explore the design particularities and performance opportunities of such an innovative building concept as CABS from a higher, strategic point of view. Moreover, it is the only one to primarily integrate and reveal the contribution of BPS techniques in such a mission. As a consequence of this novelty, the outcome cannot reflect on precedent work and further research is needed in order to enrich the practicality and effectiveness of the proposed framework. This is reasonable since the author’s intention was to guide CABS thinking towards new, uncharted directions and encourage interested parties to use, apply or even reform the developed workflow according to their desire.

On the basis of the presented demonstration study, our suggestion is against generalizations since we are not able give straightforward answers about how the optimum long-term adaptive building shell looks like and its performance potential. The concept indicates potential advantages since it can offer energy savings and upgrade the indoor environment at the same time. However, design and performance benefits can be supported when more detailed studies, elaborating solely on CABS potential under variable contexts, are conducted.

In this direction, variations in the orientation, climate or type of building are imperative while design alterations towards a more realistic model, such as more sophisticated energy systems (e.g. heat recovery ventilation, adaptive ventilation, openable windows option) or the involvement of more design variables (e.g. overhangs presence, glazing’s SHGC manipulation) may bring CABS realization a step forward. Furthermore, the utilization of multi-layer facades, in which diffusivity varies only for one of the layers or even the selection of different ranges for the investigated variables, may introduce more design freedom and bring useful insight to the integration of adaptation in building components.

Through this paper, there were multiple points when design assumptions over several available options were made, always trying for an educated and holistic approach of CABS. In retrospect though, these decisions deserve more attention and detailed addressing, especially in the prospect of future research work. The selection of the proper performance indicators and its significance was extensively mentioned in the beginning of this paper. It is interesting to explore the variables interrelations and the performance influences when more than two objectives are employed (e.g. visual discomfort). Additionally, as implied in Section 5.2, the choice of the proper indicator (e.g. ATC vs. overheating hours) is also important since it can lead to different observations, interpretations or even decisions. Therefore, due to the novelty of this concept, a more elaborate research over the profile and characteristics of performance indicators which are able to properly reveal CABS potential and the involved dynamic relations seems essential.
The actual and primary involvement of BPS and optimization techniques in this paper revealed a set of restrictions that need researchers’ attention in similar applications. The division of a simulation year into monthly intervals enhances the impact of start-up phenomena and introduces noticeable errors due to the execution of disconnected simulations. This research work quantified this error, up to a plausible degree, and it is convinced that the observations over the long-term adaptation of CABS in relation to the current traditional practice, are in a right and informed direction. Nevertheless, it would be stimulating to apply a similar strategy to a case with shorter epoch duration (e.g. weekly, daily) and analyze the design influences and the (intuitively) expected greater potential benefits of shorter time resolution. However, since the restrictions that the above mentioned start-up phenomena will impose, are going to be more intensive, new appropriate control strategies will probably be compulsory (Loonen et al., 2011).

7 Conclusion

In contrast to the initial unawareness, this paper indicates that the critical question over the way of addressing the integration of flexibility in buildings has found a persuasive answer, with the prominent aid of BPS. An upgraded sensitivity analysis process, empowered with acute information from design solutions visual observations and targeted optimization strategy, is recommended as a sensible way of detecting and understanding how design variables influence the performance of CABS, under long-term adaptation.

It is attainable to provide decision-making process, quickly and confidently, with valuable information and insight over a justified combination of adaptive and fixed variables which can successfully enable building’s value delivery. However, it remains still unclear whether it is possible to reduce CABS complexity using information and determining epoch’s characteristics (number, transition) only from a monthly sensitivity analysis process. Based on the demonstrative case study, CABS long-term performance is significantly harmed while we transit from monthly to seasonal adaptation. The question that further research should administer is whether this effect derives from the potential capabilities of long-term adaptation itself or it is assigned to the proposed framework’s weaknesses, preventing it from revealing unknown mechanisms and enabling efficient epoch selection.

Through the usage of an office zone case study, which despite its restrained applicability, enriched our understanding over CABS behavior and demonstrated, numerically, their performance opportunities, this paper’s conclusions can be briefly summarized into the following:
- BPS tools can contribute in the evaluation of Climate Adaptive Building Shells, in a structured and practical way. However, based on the scope of the analysis and research, careful consideration of the tools’ capabilities/ features and the corresponding strategies needed is decisive for eliminating possible restrictions.

- CABS long-term performance benefits can be addressed using monthly optimization iterations. Optimal adaptive CABS can be obtained by making all the possible combinations from the corresponding (out of the epochs) Pareto fronts.

- Sensitivity analysis can identify the role and behavior of design variables in the investigated objective space.

- Sensitivity analysis can successfully determine which design variables are worth being treated fixed or adaptive in long-term adaptation concept without the involvement of MOO.

- Based on the demonstration case study, monthly adaptive CABS can lead to 18 per cent energy savings and seasonal CABS to 8 per cent, on top of the best performing static design. Complexity moderation through reduction of the number of adaptive variables compromises performance of the adaptive building shells, maximum, by 3.5 per cent for a monthly (12 epochs) adaptive office zone and by 1 per cent for the seasonal (3 epochs).
8 Acknowledgements

This research was conducted in the context of a Master thesis project for the program Sustainable Energy Technology in TU/e.

9 References


Appendices

A1. Sensitivity Analysis Selection

Sensitivity analysis is a key accessory in CABS evaluation, hence the selection among the different strategies (Saltelli et al., 2005) should be carefully considered. Since the scope of this paper is to examine CABS complexity from a higher perspective, the simultaneous impact of the entire carefully chosen input group on performance outweighs that of individual input parameters (one-at-time (OAT) simulations). The use of such a multi-variate sensitivity analysis, in order the combined effect of inputs on the output to be assessed, is quite common in the building design domain (Hopfe, 2009, Vanthoor et al., 2011). Design process of building shells is a quite complex process, involving many design, physical and scenario parameters that often, the simultaneous variation of them is demanded for adding a realistic character to a simulated model. Thus, we deploy regression analysis as a SA tool because, besides the fact that it can give us quantitative measures of sensitivity, it has the vital characteristic that all inputs vary at the same time. Standardized regression coefficients (SRC) are involved in the analysis and specifically Pearson coefficients (PEAR). Although these linear regression coefficients may underperform in a non-linear model, like a CABS zone, there are preferred over rank coefficients (e.g. Spearman). They are able to convey information over the magnitude of the effect that raw values of input variables have on output ones, thus serving this paper’s goals greater.

A2. Monthly Optimization Clouds

![Monthly Optimization Clouds for January, February, March, and April]
Figure A1: Monthly scatter plots of all the available design solutions and fronts out of optimization process conducted for the office zone.
A3. Sensitivity Analysis Plots

**Figure A2:** Regression sensitivity analysis for capacity and density of the office’s external wall, displaying their correlation with both the objectives, for every month.

A4. Design Attributes in Optimization Cloud

**Figure A3:** Bubble plots of the (Pareto) optimum solutions colored based on their values of conductivity (left) and capacity (right) for April.
Figure A4: Bubble plots of the (Pareto) optimum solutions colored based on their values of conductivity for September and October respectively.