EXPLORING THE POTENTIAL OF CLIMATE ADAPTIVE BUILDING SHELLS

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ABSTRACT

Building shells with adaptive, rather than static properties, intuitively offer opportunities for both energy savings and comfort enhancements. Progress in this field is characterized by fragmented developments, and the most effective type of climate adaptive building shell (CABS) behaviour is still unknown. Therefore, also the true value of CABS is not yet determined. This paper explores and quantifies the latent potential of CABS by using building performance simulation in combination with multi-objective optimization and advanced control strategies. We conclude that application of CABS has the ability to move building performance well beyond the level of the best static building shell design.

INTRODUCTION

Improvements in design and construction of building shells plays an important role in recent efforts that aim to bridge the gap from current practice towards meeting our future energy saving targets. Notwithstanding the fact that good progress has been made, these attempts usually do not get around the status quo that building shells are typically designed as static elements in a dynamic environmental context. By being static or fixed, the conventional building shell has no means of responding to (i) the changes in weather conditions throughout the day and throughout the year, and (ii) the variable nature of occupants’ preferences.

In contrast, climate adaptive building shells (CABS) do offer the ability of actively moderating the exchange of energy across a building’s enclosure over time. By doing this in a sensible way, in response to prevailing meteorological conditions and comfort needs, it introduces good energy saving opportunities. A growing interest in CABS therefore speculates on a added value on top of passive design solutions, and considers the concept as one of possible ways to accomplish the shift towards net zero energy buildings. The concept of CABS is referred to by a multitude of ambiguous terms, including: active, intelligent, dynamic, interactive, smart etc. Throughout this paper, we use the following definition: A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behaviour over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance.

Current progress in the field of CABS is characterized by fragmented developments; either driven by specific advances in material science (e.g. switchable glazing, adaptable thermal mass and variable insulation), or originating from creative processes in design teams (Loonen 2010). Literature on CABS in relation to building performance simulation (BPS) shows the same degree of fragmentation, as it mainly deals with performance evaluations of specific case-studies such as: dynamic thermal insulation (Burdajewicz et al., 2011), and smart windows (Trčka et al., 2011). Despite these efforts, it remains unclear what type of building envelope behaviour, actually results in the best building performance.

Within research settings, it has been demonstrated recurrently that the application of optimization techniques as a design aid, can move building performance beyond the level of “trial-and-error” designs (Hopfe, 2009). Initially, these developments led to the specification of generic design rules, derived on the basis of simplified building models (e.g. Gero et al. 1983). The advent of more efficient optimization algorithms, and the continuing trend of increasing computational power, now also enables optimization studies to be performed at a higher level of detail. In recent years, optimization was successfully deployed for design of building envelopes, adapted to specific conditions and contexts. For this purpose, researchers either work with tailor-made software, or use general-purpose optimization programs coupled to detailed building performance simulation tools, like EnergyPlus (Wright and Mourshed, 2009), ESP-r (Manzan and Pinto, 2009) and TRNSYS (Chantrelle et al., 2011). The next challenging step is to bring the power of
optimization to practitioners, through development of user-friendly interfaces while respecting the aesthetics of architecture.

Since the role of optimization in CABS is thus far underexplored, the true value of making building shells adaptive is yet an unknown, and we can only guess how much of this potential is accessible with existing concepts and technologies.

The objective of this paper therefore is to increase our understanding of the true potential of CABS, by establishing the connection between optimization techniques and adaptive, rather than static building shells. As such, the focus is not on the eccentricities of individual cases, but the problem is approached from a general perspective.

The work presented in this paper follows three distinct, but complementary approaches to explore the potential of CABS. First we apply multi-objective optimization to find the best performing static building shell designs. In the second and third step, we investigate the possibility for performance improvement with CABS at two characteristic time-scales: short-term and long-term. The paper concludes by discussing some of the challenges for further work and presenting an outlook for the future.

### OPTIMAL STATIC BUILDING SHELL DESIGN

The multiple functions of a building shell are typically diverse and sometimes even competitive in nature. Harmonizing these performance requirements in a good way will therefore always remain a challenge in every project. In this paper, our scope is limited to unifying energy demand and thermal comfort. Because both these aspects prosper at each other’s expense, it is difficult to rank them in priority. In order to allow for judicious decisions, a multi-objective optimization approach is useful. The main advantage of a so-called Pareto approach is that preferences can be articulated a posteriori, i.e., after all relevant information is available.

#### Building model

The zone under investigation is a two-person perimeter office space (5.4 x 3.6 x 2.7 m), modelled according to current Dutch building regulations. The building is only occupied during office hours, and is evaluated under Dutch maritime climate. Except for the external wall, all other boundaries are assumed adiabatic. The building shell consists of one layer, with properties determined by optimization. Upper and lower bounds for the design parameters are given in Table 1. We note that this approach might lead to non-existing materials. The use of layered constructions however might approach the desired properties. In addition, we anticipate further developments through research and development in material sciences.

#### Simulation and optimization strategy

Generation of the most optimal building shell design was done by embedding TRNSYS simulations in modeFRONTIER: a commercial, general-purpose multi-objective design and optimization environment (Esteco, 2011). Among the number of available algorithms, we selected the non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002). The performance indicators, and also objectives to be minimized are:

1. The sum of heating and cooling energy demand [kJ],
2. The number of hours per year that temperature exceeds 25°C.

#### Results

Figure 1 shows the results of the whole-year simulation. In this graph, each dot represents a single building shell design. A solution is said to be Pareto optimal if, and only if it is not dominated in one or two directions by any other solution, in the decision variable space (Wang et al., 2005). In Figure 1 these Pareto designs are indicated in red.

![Scatter plot - Results of optimization for static building shell design](image)

From Figure 1, we observe a rather sparse cloud, and thus a relatively quick convergence towards optimal solutions. In addition, the plot shows a smooth trade-off curve. This means that many compromise points are feasible, and that it is up to the design team to make a rational decision, by taking their preferences into account.

Whereas the scatter plot provides a clear overview of performance aspects, it gives no insights in terms of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
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<tbody>
<tr>
<td>Density</td>
<td>50 – 8000 [kg/m³]</td>
</tr>
<tr>
<td>Surface absorptance</td>
<td>0.1 – 0.9 [-]</td>
</tr>
<tr>
<td>Thermal capacity</td>
<td>800 – 2000 [J/kgK]</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.3 – 2.5 [W/mK]</td>
</tr>
<tr>
<td>Window to wall ratio</td>
<td>0.1 – 0.9 [-]</td>
</tr>
</tbody>
</table>

*Table 1 Overview and range of design variables*
the design space. Figure 2 shows results for the same optimization run, but this time in a plot with parallel coordinates. In this figure, each line represents a single building design. The five left-most axes in the graph show the design parameters under evaluation. The two right-most axes show the performance that is associated with each of these input sets.

By using the technique of ‘brushing’ (Martin and Ward, 1995), a sub-selection of the multi-dimensional space can be visualized. This type of analysis proved to be useful in facilitating more insights in the mapping from input parameters to performance space.

By contrasting the results with lowest energy demand to those with lowest number of overheating hours, Figure 3 and Figure 4 respectively, show that the designs with high levels of comfort tend not to coincide with those that result in low energy consumption. This result indicates the existence of conflicting goals, and the inability to meet them simultaneously. Likewise, complementary analysis also revealed that there exists a disparity between designs with low heating and low cooling energy demand. Decision-makers looking for well-balanced annual trade-offs will likely find their solution of preference located in the knee-point area of the Pareto set. This outcome indicates that performance of static building shells is at best only a good compromise for the whole year. In turn, it gives rise to the hypothesis that even the best static building shells can be outperformed by CABS.

Observations
Based on the optimization study for the best performing static building shell design, the following observations can be made:

- The results of optimization tend to end up in the limits of the option space. Careful specification of possible parameter ranges is thus of primary importance.
- The best performing building shell needs to make compromises in order to satisfy performance requirements throughout the whole year. This signals clear opportunities for the use of CABS.

In the next section, the performance of the best static building shells will be compared to the performance of a CABS that is able to adjust its behaviour at relatively long time-scales.

CABS - LONG TERM ADAPTATION
Over the course of a year, meteorological conditions at a site may vary by several orders of magnitude. If building shells were able to act in response to these patterns, we expect energy savings to be readily achievable. In order to test validity of this intuitive
assumption, we take an approach that is inspired by epoch-era analysis; a method being used in flexible systems engineering (Ross & Rhodes 2008). In buildings, the ‘era’ can be seen as the building’s whole lifetime. Under dynamic conditions, like a building’s environment, this era can then be subdivided in an ordered sequence of epochs. By doing this, it creates a description of potential progression of contexts and needs over time. In each epoch, requirements and operating conditions are expected to change only within certain bounds. As such, it acts as convenient base upon which to perform analysis of value delivery over time for systems under the effects of changing circumstances and operating conditions.

Simulation and optimization strategy

In this analysis, the same reference office building as in the previous section is used. This time, the building shell is not optimized for the entire year, but in twelve epochs, each with a length of one month.

Results

Dividing the year in twelve optimization periods also implies generation of twelve Pareto sets. The outcomes of each of the simulation runs is summarized in Figure 5. All results are displayed on the same scale, with on the horizontal axes: monthly energy demand (0 – 1 GJ), and on the vertical axes: monthly overheating hours (0 – 100 h).

Figure 5 shows that both for mid-summer and mid-winter, there exists a clear progression from poor to best performing solutions. Months in intermediate seasons however, feature a real trade-off decision moment between the objectives.

![Figure 5 Overview of twelve monthly optimization runs, including Pareto sets.](image)

By making all possible combinations out of the monthly Pareto designs, optimal monthly CABS concepts can be generated for a year-round basis. This again results in a cloud of solutions with also a new Pareto set, as indicated in green in Figure 6. It should be realized that in practice most buildings are not constructed with optimal properties.

![Figure 6 Comparison of Pareto sets for CABS and static building shell design.](image)

The application of CABS however, can result in an additional significant step forward. In this case for example, if the design team accepts a number of 200 overheating hours per year, with CABS, the energy consumption for heating and cooling can be reduced by 50 per cent on top of the best performing static design.

Identifying important CABS parameters

The presented methods are not only helpful for quantifying the potential, but could also give insights in the most influential design parameters of CABS. By searching for parameters with high occurrence of cross-epoch values in the Pareto sets, one can distinguish those parameters that are most valuable to be made adaptive (Ross 2009). This would help in guiding further research efforts, and can assist in making the concept of CABS more practically feasible.

Time-scales

Dividing the optimization base in twelve monthly periods is semi-arbitrarily predetermined by the Gregorian calendar. It would be interesting to investigate the possibility and effects of more efficient transition moments, both in the design space and performance space. Likewise, it would also be interesting to examine how performance decreases with increasing optimization horizon. A façade that changes with seasons instead of months may not only offer a more subtle alternative, it also opens up options for cost-effective low-tech design solutions.

The presented method misses the opportunity to provide insights in the effects of changing configuration in response to variations with shorter time-constants. For example, the building shell cannot change its behaviour in response to daily changes in solar radiation and occupancy profiles. In principle, it would be possible to repeat this exercise by dividing the year in more periods with
correspondingly shorter optimization horizons. However, the shorter the simulation period, the larger the impact of start-up phenomena, and the larger the errors introduced by performing disconnected simulations.

Observations
Based on the results of the optimization study, the following observation can be made:

- For the present case, application of CABS can reduce energy demand by about a factor two, compared to the best performing static building shell design, while maintaining equivalent comfort conditions.

In the next section, the exploration of CABS’ potential is extended to also include the effects of adaptation at shorter time-scales.

CABS - SHORT TERM ADAPTATION
Investigating the effects of short-term adaptation in CABS introduces the need for control strategies, implemented in the simulations on a time-step basis. Because the effects of different actions are the result of interdependent physical interactions, the task of controlling CABS’ behaviour is not always straightforward. Earlier studies indicate that if-else control and other rule-based strategies are likely inappropriate for this purpose (Gyalistras et al., 2010; Coffey et al., 2010). Therefore, we continue our exploration with an optimization-driven model-based control strategy.

One of the main limitations in this approach is that not only control strategy, but also the changing building shell properties need to be introduced during simulation run-time. Most state-of-the-art BPS tools can merely cope with fixed building shells, and have no or only limited capabilities for simulation of CABS (Loonen et al. 2010; Crawley et al. 2008). This asks for workarounds, and imposes serious restrictions on the degree of freedom that can be adopted in the exploration.

Simulation, optimization and control strategy
The exploration of short-term adaptation uses the same building model as in previous analyses. Again, we selected TRNSYS as simulation tool of choice, since it offers the highest level of flexibility for performance predictions of CABS. Adaptive behaviour of the building shell was achieved in three different ways:

- Free cooling via controllable natural (night) ventilation with outside air;
- Shading via changes in shading factor;
- Insulation, by changing thermal transmittance of the facade1.

The adaptive actions were coordinated in an optimization-based control strategy by coupling TRNSYS to Matlab through TRNSYS type 155.

A graphical representation of the control strategy is given in Figure 7, and consists of the following three steps:

1. Take the value of heating or cooling load that is needed to maintain acceptable comfort conditions from the previous time-step calculation, and send it to Matlab.
2. A) Calculate the possible positive and negative contributions to the building’s energy balance, due to a change in CABS’ configuration (Table 2) according to Equations 1 to 3. B) Adjust the energy balance, depending on the mode of the building (i.e. heating or cooling) and directions of heat transfer. C) Iterate steps A and B until the set of facade properties that minimizes the sum of heating and cooling energy demand is found.
3. Send corresponding facade properties back to TRNSYS, and continue simulation for the next time-step.

<table>
<thead>
<tr>
<th>Function</th>
<th>Actuated variable</th>
<th>Driving force</th>
</tr>
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<tbody>
<tr>
<td>Free cooling</td>
<td>Flow rate ($\dot{m}$)</td>
<td>Temperature difference</td>
</tr>
<tr>
<td></td>
<td>(1 - 3 ACH$^3$)</td>
<td></td>
</tr>
<tr>
<td>Shading</td>
<td>Shading factor ($sf$)</td>
<td>Incident solar radiation</td>
</tr>
<tr>
<td></td>
<td>(0 - 0.9)</td>
<td></td>
</tr>
<tr>
<td>Insulation</td>
<td>U-value ($U$)</td>
<td>Temperature difference</td>
</tr>
<tr>
<td></td>
<td>(1.6 – 3.4 W/m²K)</td>
<td></td>
</tr>
</tbody>
</table>

$Q_{\text{free-cooling}} = (\dot{m}_t - \dot{m}_{t-1}) \cdot \rho \cdot c_p \cdot \Delta T_t$ (eq 1)

$Q_{\text{shading}} = (sf_t - sf_{t-1}) \cdot A \cdot Q_{\text{sol,t}}$ (eq 2)

$Q_{\text{insulation}} = (U_t - U_{t-1}) \cdot A \cdot \Delta T_t$ (eq 3)

The optimization run in step 2 is carried out by using Matlab’s optimization toolbox. As algorithm, we selected the genetic algorithm. The procedure for deciding on adaptive façade actions is made

\[1\] The external façade was modeled as fully glazed envelope. Thermal properties are changed by configuring multiple window types in the glazing database and varying these during runtime.
autonomously by the algorithm. As such, it is not driven by predefined priorities.

**Results**

Figure 8 shows a graph with optimal facade parameters for a typical week in summer. The graph shows that complementary actions are often needed to fulfill the demand. Further, it can be observed that for most of the time the façade properties take the value of one of both extremes.

**FUTURE PERSPECTIVES**

As it is part of ongoing research efforts, the present work rests on a couple of simplifications, and makes no attempt to give definitive statements about the theoretical potential of CABS. On the one hand, the current investigations may be too optimistic due to the use of ideal assumptions. On the other hand, it might also turn out that more advanced modelling and control strategies point towards even more advantageous prospects for CABS. This section therefore concludes the paper by discussing some of the current limitations, and expected directions for future research.

**Anticipation**

Anticipatory systems are defined as “systems containing a predictive model of itself and/or of its environment, which allows it to change state at an instant in accord with the model’s predictions pertaining to a later instant” (Rosen, 1985). In the present study, switching decisions are only based on current information on disturbances and events that happened in the past. When introduced into the control logic of CABS, anticipation can be used to examine future consequences of actions taken at the current time instant (Coffey et al. 2009). Figure 9 illustrates this concept by showing that the option with the highest performance at the present decision moment, not necessarily corresponds to the one that maximizes performance over time. In turn, this could open up several of the established advantages concerning building-related model predictive control, including:

- Making smart use of thermal inertia and variable thermal mass to attenuate peak loads and keep temperature fluctuations within the comfortable range (Hoes et al., 2011a).
- Exploiting knowledge about periodicity of occupancy and load profiles, to maximize the benefits of on/off behaviour. (Clarke et al., 2002).
- Using better timing strategies based on weather information to optimize or extend the utilization period of passive heating, daylighting, free cooling and solar shading (Zavala et al., 2009; Gyalistras et al., 2010).
Optimization under operational uncertainty
Operational uncertainty, both in terms of weather forecasts, and the way the building is actually being occupied, may significantly influence the performance of CABS. The present study just assumes perfect weather information, and only addresses a single occupancy scenario, and therefore bypasses potential performance degradation caused by such impacts. A truly optimal building shell however, is designed and operated to maintain robust performance, also in the face of operational uncertainty. Specifically developed optimization procedures, enriched with robustness indicators can help to explore this problem (Hoes et al., 2011b).

Objective functions
The present decision making process makes use of automated optimization, driven by objective functions. This implicitly requires that ‘optimal performance’ needs to be captured in a formal mathematical expression. Apart from addressing the question what optimal performance actually might be in terms of comfort, we realize that it is important to focus on the maximum acceptable rate-of-change as well. In addition, the exploration is now biased towards extreme solutions. It would be interesting to examine the potential of near optimal solutions. Although slightly sacrificing performance, such designs may be achieved in practice with less challenging technology.

Thermal and daylight
In the present study, all optimization efforts were directed towards the bi-objective compromise between energy demand and thermal comfort. In real-world cases however, performance of a building shell is determined by more aspects. It will always remain challenging to introduce e.g. aesthetical and structural concerns into computational optimization algorithms, but the extension towards day lighting is considered viable. Provisioning of daylight plays a prominent role in the interplay of physical interactions at the building’s interface. At times, it may replace artificial lighting, provide views and passive solar gains, but also the risk for glare, radiant asymmetry and privacy losses. Taking daylight into account will therefore facilitate a better representation of reality. Introducing visual comfort as a third objective, will likely shift the optimal point for energy demand and thermal comfort, in either positive or negative direction. An integrated approach with dynamic daylight and thermal simulations is essential to gain these insights.

Usability of the results
The present work intentionally remains at an abstract level, without discussing the specifics of a case-study building in detail. The authors realize that it might be difficult to envision direct applications for the presented results. Instead, this study hopes to make a contribution towards longer-term goals, e.g. by setting a performance bound. As such, we foresee a novel application area for the use building performance simulation. Insights obtained by the simulations can be used as an instrument for strategic decision making. In addition, it helps in specifying most valuable directions for future research and development. This approach is sometimes characterized by the term ‘inverse’ as it marks the shift from merely answering “what-if” questions towards providing guidance into “how-to” type of problems.

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REFERENCES


