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# Framework for assessing the performance potential of seasonally adaptable facades using multi-objective optimization

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ABSTRACT

Climate adaptive building shells (CABS) are receiving increasing attention because they can enable high-performance building design that combines low energy consumption with good indoor environmental quality (IEQ). Various studies have acknowledged the potential of CABS with seasonal adaptation, but thus far, there is no method available to quantify their performance potential. This paper presents a framework for design and performance analysis of CABS with optimal seasonal adaptation strategies. The framework is based on a sequence of multi-objective optimization scenarios and uses a genetic algorithm in combination with coupled building energy and daylighting simulations. Findings from a case study with an office building in the Netherlands demonstrate the effectiveness of the framework in quantifying the potential of seasonal CABS. Results of the case study show that monthly adaptation of six facade design parameters can lead to improved IEQ conditions and 15–18% energy savings compared to the best performing non-adaptive building shell. Through post-optimization analysis of monthly and annual solutions, a better understanding of the key elements of seasonal facade adaptation is obtained.


## 1. Introduction

There is a growing interest for buildings with adaptable facade elements which are capable of dynamically adjusting their properties in response to variable ambient conditions and occupants' comfort preferences [1–6]. Through enhanced interaction with the environment, climate adaptive building shells (CABS) seek the reduction of energy demand for heating, cooling and lighting, while maintaining high levels of indoor environmental quality [7].

So far, most attention has been given to research, design and development of CABS that can change their properties on a high-frequency basis, e.g., seconds, minutes or hours [8]. Examples include the deployment of switchable glazing technology [9], dynamic thermal insulation [10], advanced solar shading systems [11–13], and materials with variable solar absorptance/emittance properties [14]. These short-term adaptation mechanisms enable the facade to change in direct response to the varying conditions, and as a result, they are expected to present the highest potential in terms of performance improvements [15–17]. In terms of complexity, however, the application of short-term CABS is often assessed as less favorable because it typically requires relatively complex and expensive technologies [7]. Moreover, the control of short-term CABS in the operational phase is rarely a trivial task, and problems during operation may have an adverse effect on CABS performance [18–20]. In view of these aspects, it can be argued that in many construction projects the option of short-term CABS is regarded as inferior to more conventional facade technologies [21].

An alternative to short-term CABS are facades that can adapt their behavior in response to changing conditions over the seasons [22]. Previous studies have indicated that building designs with seasonal adaptation strategies can, in principle, enhance energy and comfort performance compared to the best static situation. Improvements in building performance have been demonstrated in cases with seasonal variation in, for example: solar shading design [23–25], window properties [26–30], thermal insulation [31], thermal mass [32], natural ventilation strategies [33,34] and temperature set points [35]. Compared to short-term adaptability, the feasibility of long-term CABS is expected to be higher, as long-term CABS are more likely to be built as low-cost add-on solutions, with less challenging technologies and simpler controls [15].

Despite the promising perspective, there is still little information available that quantifies the relationship between long-term adaptable facade principles and potential building performance improvements. No study has addressed this issue from a higher-level perspective, focused on a methodology to quantify the

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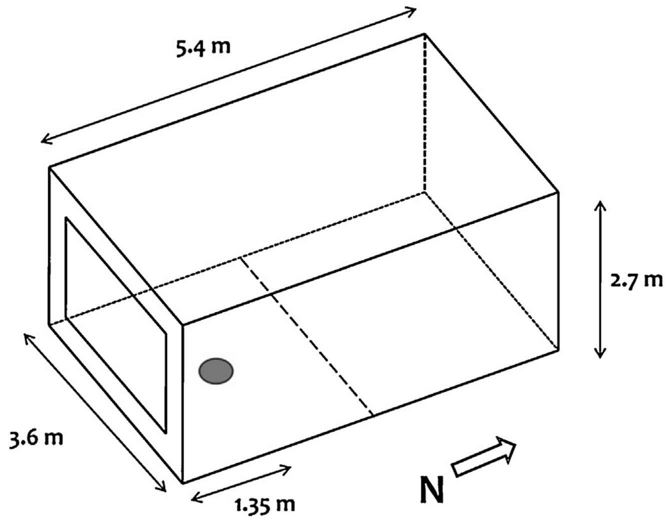


**Fig. 1.** Schematic overview of the investigated office zone model. The position of the work plane (grey circle) is situated in the south-oriented half of the zone.

performance potential of seasonal building shell adaptation. This potential must be based on optimum adaptable building shell properties, but there is no method available to guide designers towards a systematic and effective assessment of optimum long-term CABS properties.

This paper presents a method for quantifying the impact of seasonal facade adaptation on building performance, based on coupled building energy and daylight simulations, conducted under multi-objective optimization (MOO) scenarios with genetic algorithms. This method is described by means of a case study, which assesses the improvement in energy performance and indoor environmental quality due to monthly adaptation of six building envelope parameters. The work in this paper aims to increase understanding of the feasibility of long-term adaptable facades as a design strategy, by analyzing the mutual influence between design and performance aspects from a higher level perspective, i.e. the potential of long-term CABS concepts. Actual implementation aspects and specifics of innovative materials and building envelope components are not within the scope of this study, but could be explored on the basis of the results we present here.

This paper is structured in four sections, as follows. Section 2 describes the methodology adopted for the quantification of long-term CABS performance in the case study, including details of the case study building, performance indicators and strategies for simulation and optimization. In Section 3, results of the case study are presented and analyzed. Finally, Section 4 reflects on the findings of this work, and provides directions for future research.

## 2. Methodology

### 2.1. Case study building model

The zone under investigation (Fig. 1) is a single-person south facing perimeter office zone (3.6 m × 5.4 m × 2.7 m). The zone is situated at an intermediate floor and surrounded by identical office zones and a corridor at the back. The building, which is evaluated under Dutch climate conditions, is occupied on weekdays from 8 to17 h. Heating is supplied with an ideal system with unlimited capacity, but no active cooling system is employed. Ventilation with outside air (no heat recovery) is provided at a rate of 2 ACH during occupied hours. The opaque part of the external facade is modeled as a single layer with a thickness of 0.35 m. Window-to-wall ratio (WWR) as well as thermophysical and optical material properties

**Table 1**
Overview and range of design parameters.

| Parameter | Range | Unit |
|---|---|---|
| Density ($\rho$) | 50–3000 | [kg/m$^3$] |
| Specific heat ($c_p$) | 0.8–2.0 | [kJ/kg K] |
| Thermal conductivity ($\lambda$) | 0.1–2.5 | [W/m K] |
| External surface absorptance ($\alpha$) | 0.1–0.9 | [–] |
| Window to wall ratio (WWR) | 0.1–0.8 | [–] |
| Glazing ID | 1–7 | [–] |

are determined by optimization. Table 1 gives the adaptable design parameters, together with the upper and lower bounds.

Allowing the different glazing properties to vary independently from each other can easily lead to fenestration typologies that are unrealistic from a physical point of view. To avoid this, we used existing window systems with meaningful properties. Table 2 shows the detailed properties of the glazing types that correspond to the glazing IDs from Table 1.

An external shading system is applied to control the solar gains. Venetian blinds are “ideally” controlled on the basis of an active users profile [36]. This stochastic algorithm assumes that the blinds are rearranged on a regular basis with the aim of maximizing daylight availability while preventing glare and direct sunlight on the work plane [36]. Artificial lighting with a lighting power density of 10 W/m$^2$ is switched on/off, only when daylight availability is not sufficient to meet the illuminance target of 500 lx on the work plane (Fig. 1).

### 2.2. Performance indicators

#### 2.2.1. Energy performance

The energy saving potential of the investigated case study is assessed by considering the zone’s primary total energy consumption, which is composed of the energy required for heating (central heating efficiency factor 0.65) and artificial lighting electricity (power plant efficiency factor 0.4). An active cooling system is not considered in this case study, therefore cooling energy does not contribute to the energy demand. Energy consumption for artificial lighting is not fixed during the operation of the office but varies with daylight availability in accordance with the different building shell configurations.

#### 2.2.2. Indoor environmental quality

Thermal comfort is evaluated using an adaptive thermal comfort (ATC) indicator [37]. The method is mainly intended to assess naturally conditioned spaces, like the office investigated, and presents specific advantages over the more traditional comfort metrics, which make it an appropriate indicator for high-performance building design in moderate climates [38,39]. As the heating system is assumed to have unlimited capacity, there is no thermal comfort problem regarding heating. The building has no active cooling system, and thermal comfort performance is measured by the number of overheating hours during occupied hours.

The heating system in the zone is controlled on the basis of indoor air temperature, with a set point 0.5 °C above the lower

**Table 2**
Overview of the glazing properties.

| Glazing ID | *U*-value [W/m$^2$ K] | *g*-value [–] |
|---|---|---|
| 1 | 5.7 | 0.86 |
| 2 | 2.8 | 0.76 |
| 3 | 1.4 | 0.59 |
| 4 | 1.4 | 0.62 |
| 5 | 1.3 | 0.59 |
| 6 | 1.3 | 0.62 |
| 7 | 0.9 | 0.59 |