# Energy saving potential of climate adaptive building shells - Inverse modelling of optimal thermal and visual behaviour

*Citation for published version (APA):*
de Boer, B. J., Ruijg, G. J., Bakker, L. G., Kornaat, W., Zonneveldt, L., Kurvers, S. R., Alders, N., Raue, A., Hensen, J. L. M., Loonen, R. C. G. M., & Trcka, M. (2011). Energy saving potential of climate adaptive building shells - Inverse modelling of optimal thermal and visual behaviour. In *Adaptive Architecture, an international conference, London*

*Document status and date:*
Published: 01/01/2011

*Document Version:*
Accepted manuscript including changes made at the peer-review stage

***Please check the document version of this publication:***

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• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Download date: 04. Oct. 2023

Boer, B. d., Ruijg, G. J., Bakker, L., Kornaat, W., Zonneveldt, L., Kurvers, S., Alders, N., Raue, A., Hensen, J. L. M.,
Loonen, R. G. C. M. and Trcka, M., 2011.
Energy saving potential of climate adaptive building shells - inverse modelling of optimal thermal and visual behavior.
Proceedings of the International Adaptive Architecture Conference, London, 3-5 March, pp. 16.

# Energy saving potential of climate adaptive building shells - Inverse modelling of optimal thermal and visual behaviour

[1]Bart de Boer, Gerrit Jan Ruijg

Energy research Centre of the Netherlands (ECN), PO Box 1, 1755ZG Petten
The Netherlands

b.deboer@ecn.nl T: 0031(0)224564901

[2]Leo Bakker, Wim Kornaat, Laurens Zonneveldt

TNO Bouw en Ondergrond, PO Box 49, 2600 AA Delft, The Netherlands

leo.bakker@tno.nl

[3]Stanley Kurvers, Noortje Alders, Arjen Raue

Delft University of Technology, Faculty of Architecture, Section Building Technology, Climate Design

[4]Jan Hensen, Roel Loonen, Marija Trcka

Eindhoven University of Technology, Unit Building Physics and Systems, PO Box 513, 5600 MB
Eindhoven, The Netherlands

r.c.g.m.loonen@tue.nl

## Biography

Since 1998, Bart de Boer has been working as researcher and project manager at the Energy research Centre of the Netherlands (ECN). With the background of a building engineer, he is an expert in the field of Energy in Buildings. He has an extensive research experience in the fields of Active Facades (Smartfacade, FACET), Passive house concept (PEP), Building Integrated Photovoltaics (PV Performance) and Energy Performance directive (EPG commission). He participates as researcher and project manager in many national and international R&D and knowledge dissemination projects, in close collaboration with industry, universities and other research institutes.

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## Abstract

In common building design practice energy performance calculation programs or, in the best case, dynamic building simulation programs are used to optimize the properties of a building shell. However, even with use of dynamic building simulation programs adaptive behaviour, in terms of changing building shell properties, is not easy to simulate since many inputs - like insulation values, window ratio, etc. are ‘fixed’ values. The result of these optimization calculations is therefore rather an optimization in fixed design values then a set of ideal optimal adaptive behaviour building shell parameters.

In the Dutch FACET project (Dutch acronym: ‘Adaptive façade technology for increased comfort and lower energy use in the future’) a quest for the ideal building shell with adaptive, variable properties is performed. Since the standard way of simulating does not allow fully adaptive building shell behaviour, a completely new, inverse modelling approach is set up. The key question here is: “What would be the ideal, dynamic properties of a building shell to get the desired indoor climate at variable outdoor climate conditions?”

By reversing the design approach, and using inverse modelling, a set of ideal, hypothetical building shell parameters is computed for different climate conditions at various time steps (seasons, day-night, instantaneous), for different building categories like offices, schools and dwellings. This ‘ideal’ adaptive behaviour will make it possible to maximize indoor comfort and to minimize energy use for heating, cooling, ventilation and lighting. It does not start with having existing concepts in mind, but instead focuses on clarifying the theoretical potential of adaptive architecture.

In the TRNSYS and Radiance simulations the building shell input is given as a black box, with a wide range of possible (combinations of) thermal and visual properties. Technologies and materials to meet the requirements can be more futuristic but also very ‘down to earth’. Partial solutions are already available, in low or high tech solutions, such as smart glazing, variable vacuum insulation, insulating window covering, etc. Further technology development is expected to be desired to fully meet the ideally adaptive behaviour requirements.

Based on state of the art ‘adaptive temperature’ criteria optimal thermal behaviour was simulated in a first step. This gives the energy saving potential for an optimal thermal adaptive building shell. In a second step the computed optimal daylight characteristics of the building shell is given by optimizing visual comfort in Radiance. In a next step, both visual and thermal behaviour is optimized in an integral way, using a multi objective criteria approach.

This paper describes the thermal and visual simulation optimization results of the FACET project. Preliminary results show that optimal adaptive building shell properties can reduce the total heating and cooling demand by a factor 10 compared to state of the art new built offices. For the Netherlands this means a factor 3 compared to the very efficient passive house technology. In the case of offices the heat demand is practically eliminated and the cooling demand can be reduced significantly by a factor two. The resulting extremely low energy demand means that less effort is needed to enable zero energy, or energy producing buildings in the future.

## 1. Introduction

Most of currently designed and constructed building shells are fairly static systems which are not designed for optimal energy performance and/or optimal indoor comfort. Properties like insulation level, thermal mass and window area are fixed values and practically kept constant throughout the year. Fixed or adjustable external shading devices are often not used and windows with low g-values are used instead. Visual comfort is in many cases regulated by hand with indoor lamellas.

Although energy performance regulation is forcing the building sector to improve the energy performance of buildings, there is still a need to drastically improve energy efficiency. Especially in the existing building stock, much is still to be gained. The energy performance of (new) buildings is in practice based on the mandatory, minimum demands, because for project developers there is no benefit to go beyond this level. Up till now this results in buildings of rather poor energy performance, with high energy bills for the end user. To meet the requirements of indoor comfort criteria, buildings are actively climatised by installations. Heating, ventilation, air conditioning (HVAC) and lighting installations are additionally needed to meet the requirements. Air-conditioning not only results in high energy use, it often leads to discomfort.

In common design practice energy performance calculation programs or, in the best case, dynamic building simulation programs are used to search for the building shell with the highest performance. Different options for façade constructions are compared to retrieve the best result in energy use. This leads to solutions for a fixed design for window size, g-value, insulation value, etc.

The key feature of the FACET project is the inverse modelling approach. Starting point is the ideally desired physical behaviour of an adaptable building shell. After determining this ‘ideal’ thermal, visual and ventilation behaviour the next challenge is to create concepts which are able in practice to fulfil the requirements of adaptive behaviour in time scales of seasons, days, hours or instantaneous.

### *1.1 Climate Adaptive Building Shell (CABS)*

Since the energy crisis in the early 70’s the glass industry came up with many new products to improve the image of glass. A study for glass manufacturer Pilkington resulted in ‘A wall for all seasons’ by Mike Davies (Davies, 1981). His pledge for a polyvalent wall undoubtedly had a big influence on further façade developments. This polyvalent wall should control and regulate energy flows by itself including the needed energy (Haartsen et al, 1999).

Climate adaptive building shells (CABS) have received growing attention in the last years (Ritter, 2007; Klooster, 2009; Loonen, 2010a; Schumacher et al., 2010). For the project FACET the definition of CABS is: “a climate adaptive building shell can adapt itself to the needs of the user of the building and to the changing climatic conditions to which the building skin is exposed, while at the same time the energy use needed for maintaining desired comfort is minimized.” Concepts are mostly focused on the façade and are also known by names as ‘smartfacade’ (Boer, de, 2008), ‘active facade’, ‘dynamic facade’ and ‘intelligent facade’.

In 2006 a set of research questions was composed by Rien van der Voorden which formed the basis of the latter FACET project. From 2008-2009, a study on the inverse CABS approach was performed. This previous work already indicated the large energy saving potential of CABS/FACET (Bakker 2009). In the FACET project the aim is to bring climate adaptive building shells to a higher level by, in a first step, sketching the ideal adaptive behaviour of a building shell. This is done by means of inverse modelling: the theoretically ideal desired properties of a building shell are determined, within a wide range of possible parameters. In a next step in the project, CABS proof of concepts will be composed to meet the ideal requirements as much as possible.

### *1.2 FACET: inverse modelling approach*

In the FACET project an up till now new, inverse modelling approach is applied by asking the question: “What would be the ideal, dynamic properties of a building shell to get the desired indoor climate at variable outdoor climate conditions?” By reversing the business as usual design approach, a set of ideal, but realistic building shell parameters is computed for different climate conditions at various time steps (seasons, day-night, instantaneous).

The idea of an inverse approach can be translated as ‘turning around’ the order ‘input => model/simulation => output’ as depicted in the figure below.

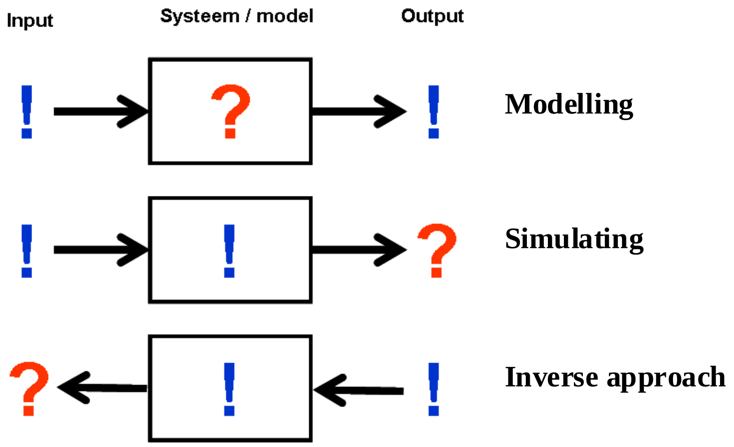


*Figure 1: Schematised representation of the inverse approach*

In contrast to normal simulation work the input at the inverse simulation approach is an unknown variable (= ?) with a desired known (= !) output. In this case, dynamic instead of static building properties (such as U value, solar transmittance, ventilation rate, etc.) are needed. By defining the desired output, in theory, the inverse simulations will calculate which building shell properties (within an acceptable range of values) are needed to stay within the defined comfort zone at the lowest energy use.

The development of fully climate adaptive buildings shells, with theoretically ‘ideal’ adaptive behaviour enables the end-user to maximize indoor comfort and to minimize energy use for heating, cooling, ventilation and lighting. Technologies to reach this ‘ideal’ behaviour are partially already available, in either low or high tech solutions, such as smart glazing, variable vacuum insulation, insulating window coverings, etc. However, further technology development is desired to fully meet the requirements. Outcomes of this project help to identify the most promising research directions.

In the FACET project the desired properties with regards to 1) thermal optimization and 2) visual optimization are at first separately addressed, and will come together in the run of the project, to reach integral optimization. In this paper first the program of requirements for visual and thermal comfort are sketched. Next, the results of the separate visual and thermal optimization will be given. In the last chapter the ongoing perspective of employing multi-objective optimization (MOO) techniques for integral, inverse visual and thermal optimisation is presented.

## 2. Program of requirements: visual and thermal comfort

In this chapter the requirements for respectively visual and thermal comfort are given, based on state of the art for offices. In a later stage in the FACET project also the requirements for other applications like schools and dwellings will be given.

### *2.1 Requirements: visual comfort*

The definition of state of the art requirements for visual comfort, at an office application, are summarized in table 1.

| Mimimal illumination level | 200 lux |
|---|---|
| uniformity | > 0.5 |
| illuminance level visual task | > 500 lux |
| maximum luminance | 3000 cd/m2 |
| luminance ratio visual task - direct surounding | 1:3 |
| luminance ratio visual task - room | 1:10 |
| luminance ratio visual task - exteror view | 1:30 |
| visual contact with exterior | > 5% |

*Table 1 Visual performance requirements*

The amount of light required on the work plane depends on the specific visual task. For office work 500 Lux with a uniformity of 0.7 is a minimal requirement.

The maximum luminance ratio between the visual task and the direct surroundings is 1:3. The luminance ratio between the visual task and the room surface is 1:10. Luminance ratios between the visual task and the exterior view is 1:30.

### *2.2 Requirements: thermal comfort*

To be able to define “state of the art” requirements for the indoor environment a literature review was performed. More than 120 scientific papers were studied. A wide range of conclusions were drawn and the most relevant can be summarised as follows:

- Thermal comfort can be reached within a bandwidth that is wider than traditional climate chamber models suggest;
- Narrow temperature bands do not result in higher levels of thermal comfort;
- Thermal comfort is not a product of an HVAC-system, but a goal that should be reached by the interaction between building, the building systems and the occupants;
- Occupants do want to feel comfortable and should have opportunities to bring the indoor environmental temperature as close as possible to their comfort temperature;
- Buildings should allow occupants to control their environment by having opening windows, adjustable shades and fans;
- The thermal history and the thermal behaviour of the building influences the thermal expectations of the occupants;
- Occupants prefer a slightly varying indoor environment over a stable temperature.
- The indoor temperature should relate to the outdoor temperature.

Next requirements for thermal comfort were derived, based on the literature review, and experiences of occupant satisfaction surveys and building surveys.

*Comfort temperature:*

- The operative temperature should be within the given bandwidth of fig. 1 for 95% of the occupied time.

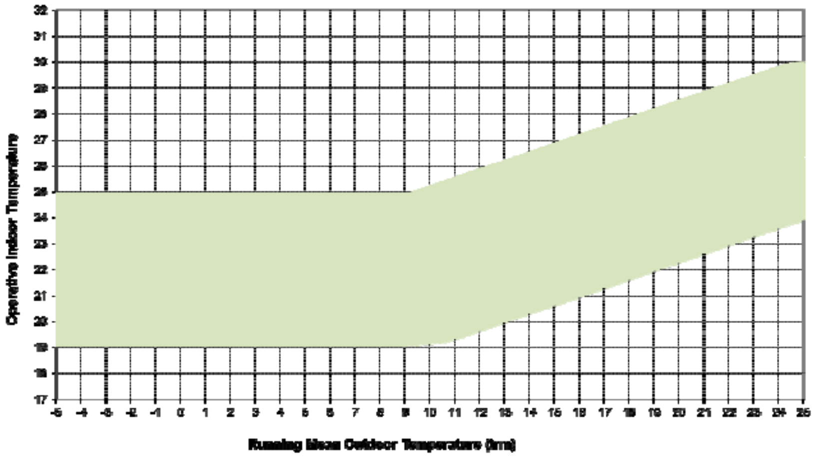


*Figure 2: Bandwidth of the operative comfort temperatures related to the Running Mean Outdoor Temperature $t_{rm}$.*

On the vertical axis the operative temperature is given. On the horizontal axis the Running mean Outdoor temperature is given:

$_{n}t_{rm} = 0{,}2.t_{od-1} + 0{,}8._{n-1}t_{rm}$ (°C)

$_{n}t_{rm} =$ Running mean outdoor temperature on day n, and $_{n-1}t_{rm}$ of the preceding day.

$t_{od-1}$ = Mean of the daily maximum and daily minimum temperature of yesterday.

The bandwidth is limited by:

$\Theta_i \max = 0{,}33\Theta_{rm} + 21{,}8$ (°C)

$\Theta_i \min = 0{,}33\Theta_{rm} + 15{,}8$ (°C)

*Free Running mode:*

The climate system (building and services) is “free running” over a large as possible range of the ‘running mean outdoor temperature’ ($t_{rm}$), that is active heating and cooling is to be avoided as much as possible. To achieve this, the design is optimized by:

- Utilizing desired and avoiding unwanted solar warmth;
- Utilizing thermal inertia;
- Implement operable windows, night-time ventilation, sun shading, etc.;

*In the operational phase:*

- When at a low $t_{rm}$ the lower comfort limits are being exceeded, heating is applied;
- When at a high $t_{rm}$ the upper comfort limits are being exceeded, occupants should have adaptive opportunities like controllable ceiling fans;
- When at a high $t_{rm}$ the upper comfort limits are being exceeded, occupants should have adaptive opportunities like operable windows and controllable ceiling fans;

When at a high $t_{rm}$ the upper comfort limits are being exceeded and adaptive opportunities like operable windows and controllable ceiling is not effective or possible, active (sustainable) cooling is utilized, fans;

The operative temperature variation within a day is limited to 4K and the variation of the operative temperature between days limited to 1K and 3K over a week. For thermal comfort, more requirements are given, like the maximum temperatures in winter to maintain a good perception of the indoor air quality perception.

## 3 Thermal optimisation: dynamic simulation using adaptive control strategy

### *3.1 Inverse modelling approach*

For the TRNSYS simulations the office room (at North and South orientation) was modelled, using an adaptive control mechanism, called Qcor:

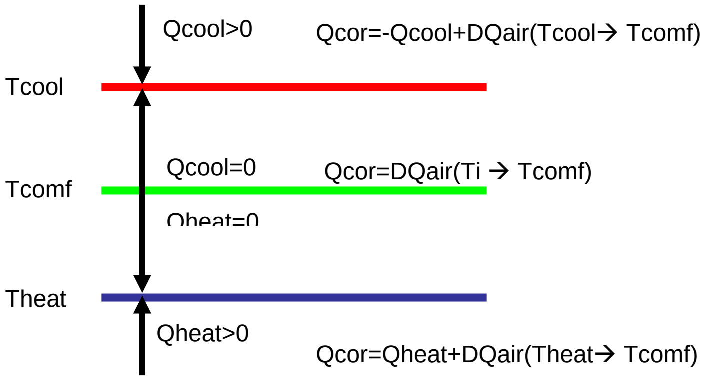


Figure 3 Strategy of control mechanism for Qcor

To be able to simulate the energy performance of the FACET façade with TRNSYS it would be necessary to model construction materials with variable thermal conductivity, but TRNSYS does not provide a possibility to change parameters of materials during simulations. However, TRNSYS does provide the possibility to choose another type of glass during simulation, by entering another glass ID. This makes it possible to change the properties of the glass in steps, what is just slightly less accurate than continuously adjustable properties. It appeared to be possible in TRNSYS to create a "glass" with a solar access factor (g-value) of 100% and free to choose heat conductivity. So 11 different "window panes" are created with heat conductivity ranging from 0.1 to 100 ($m^2$.k)/W, spread in a logarithmical way over the range. A control strategy called Qcor then chooses the most appropriate "glass" from the library and adjusts the external shading, ventilation and heat recovery bypass in a way that the temperature is as close as possible to the comfort optimum.

The range of variable values for the FACET office room and the fixed values at the reference office room are given in Table 1. By creating a virtual window with wide ranges of transparency in combination with a wide range of insulation values the façade is able to serves as a black box.

Table 1. Range of variable and fixed façade properties

| | FACET office | Reference office |
|---|---|---|
| Rc (m2.K)/W | 0.01 <=> 10 | 4,6 m2 HR++ glass (u=1,1 W/m2K)<br>8,1 m2 closed, Rc= 3 (m2.K)/W |
| shading (-) | 0 <=> 0.98 | 0,9 (south)<br>0 (north) |
| Heat recovery vent. (%) | 0 <=> 95 | 70 |
| ventilation (dm3/s) | winter 5 <=> 20<br>summer 5 <=> 80 | (winter: 1,9 [1/h])<br>35 (summer: 2,4 [1/h], +1K)<br>36,5 (extra: 2,5 [1/h], +2K) |

### 3.2 Results

The TRNSYS simulation results are depicted in

Figure 4 below. When simulated in TRNSYS the energy demand of the reference new built office turns out to be about 60 MJ/m$^2$, The energy use of the FACET office is with 8 MJ/m$^2$ a factor 8 lower than the reference office, what indicates that large energy savings appear possible compared to nowadays standards.

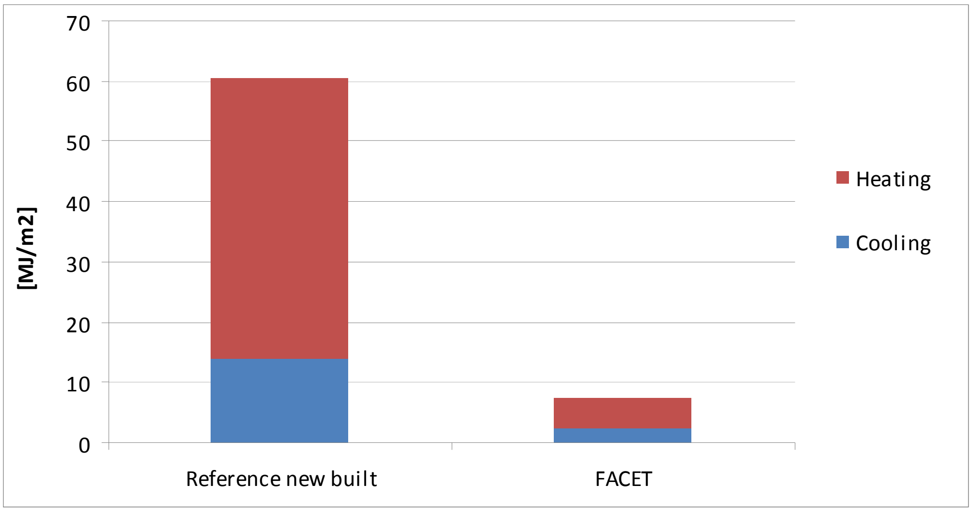


Figure 4 Heating and cooling demand of reference new built office and FACET office

As can be seen in the figure below, the indoor temperature throughout the year is 99.5% of the time within the specified ‘90% satisfactory’ boundaries of the adaptive temperature gradient. This means that a high comfort level is achieved in combination with a very low heating and cooling demand. It should be noted that the extra energy needed for ventilation is not included here. If natural ventilation is possible this will not affect the energy consumption but in the case of mechanical ventilation this can become a relatively important part.

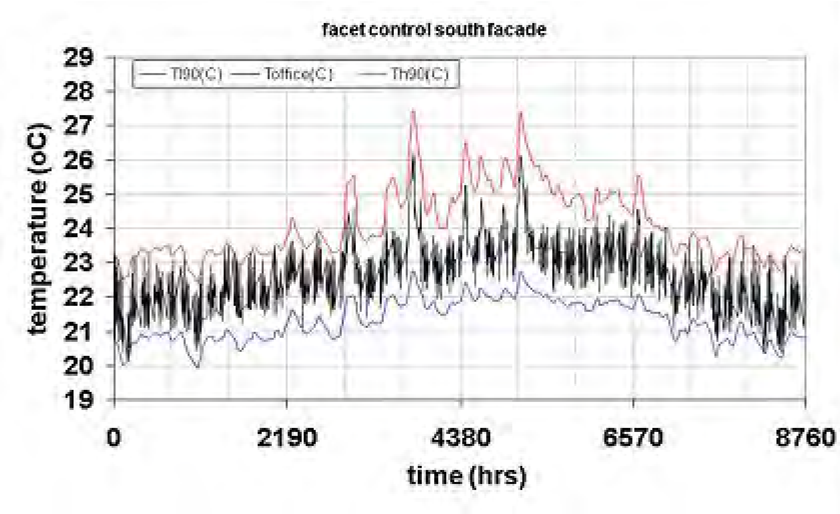


Figure 5 Indoor temperature 99,5% within ’90% satisfactory’ boundaries of adaptive temperature gradient

The next step in this analysis will be to integrate and optimise the preferred settings for both thermal and visual comfort. Also other building types like schools and dwellings will be simulated. The integrated approach will be performed using a multi-objective optimisation modelling method, as described in the next part of the paper.

## 4 Visual optimisation: inverse simulation using performance indicator

The ideal virtual daylight façade always realizes the optimal possible daylight performance taking into account the visual contact with outdoors. The light transmitting properties, as the spectral and angular transmittance and reflectance per façade position or segment are optimized to realize the best possible configuration offering the best possible visual performance.

### *4.1 Performance function*

To find the optimal façade properties for various conditions a performance function is defined.

This is in principle a so called cost function. If parameters are within the limits defined by the boundary conditions, the output of the performance function equals zero. If a value exceeds the levels defined in the boundary conditions a penalty is given proportional to the level the boundary condition is exceeded. Since the sensitivity of the human eye is logarithmic, the logarithmic value is used as penalty. The total penalty is the sum of all penalties. Based on this performance function, Genetic algorithms are used to find the best solutions within this complex problem.

### 4.2 Superposition approach

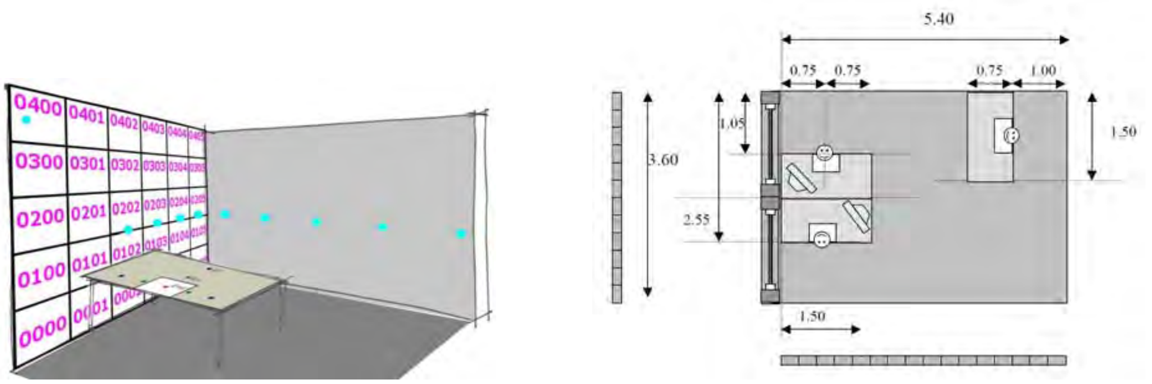


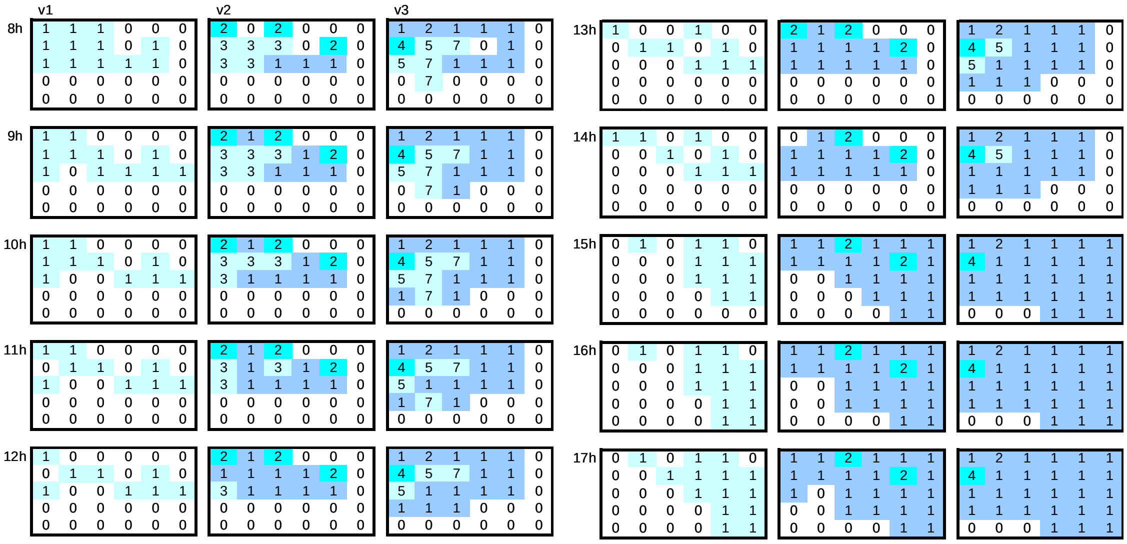
Figure 6 Facade with 30 independent elements with different optical properties (left) and the used office model (right)

For the simulations, the computer program Radiance is used. Because genetic algorithms require a relative large number of computations to find optima and because Radiance requires a relative large number of computations per case this combination would result in very long computation times. Therefore a method based on superposition is utilized. Various indoor luminance and illuminance sensors are defined within the example office.

In this first study, a façade with 30 elements with independent variable transmission is assumed. There are three variants assumed. Binary (visual transmittance of 1 or 0,), 4 stages (transmittance of 0, 1/3, 2/3 en 1) and 8 stages (visual transmittance of 0, 1/7, 2/7, 3/7, 4/7, 5/7, 6/7, 1).

### 4.3 Results

The contribution from all 30 elements is determined using Radiance element by element resulting in a response matrix. The expected sensor readings from a combination of opened elements result from superposition. TNO developed a tool which enables validating over 100.000 variants within the optimization loop in a few minutes.



| | v1 | | | | | | v2 | | | | | | v3 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8h | 1 | 1 | 1 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 |
| | 1 | 1 | 1 | 0 | 1 | 0 | 3 | 3 | 3 | 0 | 2 | 0 | 4 | 5 | 7 | 0 | 1 | 0 |
| | 1 | 1 | 1 | 1 | 1 | 0 | 3 | 3 | 1 | 1 | 1 | 0 | 5 | 7 | 1 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9h | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 |
| | 1 | 1 | 1 | 0 | 1 | 0 | 3 | 3 | 3 | 1 | 2 | 0 | 4 | 5 | 7 | 1 | 1 | 0 |
| | 1 | 0 | 1 | 1 | 1 | 1 | 3 | 3 | 1 | 1 | 1 | 0 | 5 | 7 | 1 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 1 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10h | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 |
| | 1 | 1 | 1 | 0 | 1 | 0 | 3 | 3 | 3 | 1 | 2 | 0 | 4 | 5 | 7 | 1 | 1 | 0 |
| | 1 | 0 | 0 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 0 | 5 | 7 | 1 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 7 | 1 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11h | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 |
| | 0 | 1 | 1 | 0 | 1 | 0 | 3 | 1 | 3 | 1 | 2 | 0 | 4 | 5 | 7 | 1 | 1 | 0 |
| | 1 | 0 | 0 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 0 | 5 | 1 | 1 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 7 | 1 | 0 | 0 | 0 |
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| 12h | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 |
| | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 2 | 0 | 4 | 5 | 7 | 1 | 1 | 0 |
| | 1 | 0 | 0 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 0 | 5 | 1 | 1 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
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| 13h | 1 | 0 | 0 | 1 | 0 | 0 | 2 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 |
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| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14h | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 0 |
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| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
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| 15h | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
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| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| 16h | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 4 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| 17h | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 4 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |

Figure 7 Overview of the results for the three variants (period

### *4.4 Conclusions*

The method is suitable within the FACET reverse approach. Superposition approach with pre-processed Radiance output shows an effective way to enable evolutionary optimizations. The results provide feedback on the defined demands. There are many variants with similar performance output. The method will be extended with among other more working positions and light deflecting properties of the façade elements. In addition, full scale tests will be executed to get feedback on the user experience on FACET facades.

## 5 Integral thermal and visual optimization: dynamic multi objective optimisation

The multiple functions of a building shell are found to be diverse and sometimes even competitive in nature. Harmonizing the performance requirements in a good way therefore continues to be a challenge in both static and adaptive building designs. The pivotal point in control of CABS is identified to be the behaviour of the transparent facade elements. Both inverse modelling approaches presented thus far in this paper provide some essential steps that increase our insights in these complex phenomena. A main limitation however is that thermal and visual aspects are considered in isolation. These methods are therefore not able to map the mutual influences in the trilateral relationship between thermal performance, visual performance and energy performance. As a result, it bypasses the interrelated coupling between e.g., glare, electricity consumption for artificial lighting, risk for radiant asymmetry, view to the outside, shading control, thermal loads etc. Effects of such a simplification are also perceptible in the end results of the inverse simulations. The way in which optimal facade behaviour is defined thus far focuses on only one domain, and thereby introduces a bias towards that single performance aspect. Outcomes of the optimization tend to be out of balance and conflicts among objectives are overlooked. Because we are not able to find the good compromise solutions, we argue that the presented inverse methods cannot fully disclose the true potential of CABS.

To overcome these limitations, we propose an alternative method in this section, which will be used in our search for the optimal behaviour of dynamic façades. This strategy relies on the principle of incorporating Pareto optimization in the decision making process (Hopfe, 2009). The remainder of this paper introduces and motivates this principle, elaborates more on the envisioned simulation strategy, and finally discusses some of the challenges that need to be resolved in this ongoing research effort.

### *5.1 Pareto optimization*

The traditional way of trading-off multiple criteria in design decision making is to assign relative preferences to each of the relevant objectives. Such a weighted sum approach results in a single function for overall performance, similar to cost function for light in the previous section. Optimizing for this aggregate function therefore simplifies the multi-attribute decision problem into a single-objective one. A major drawback of this method is that the degree of compensation between criteria is (i) arbitrarily determined and (ii) fixed beforehand. (Das and Dennis (1997); Scott and Antonsson (2005)).

Multi-objective optimization on the other hand, is a formal mathematical method that deals with concurrent minimization and/or maximization of objective functions (e.g. energy demand (minimization) and thermal or visual comfort (maximization)) by changing the decision variables of a problem (in this case thermophysical and optical properties). A solution is said to be Pareto optimal if and only if it is not dominated by any other solution in the decision variable space (Wang 2005). In other words, this method leads to a set of solutions (Pareto frontier) that are not outperformed by other solutions for each particular objective.

Figure 8 provides a schematic representation of such a trade-off curve for two objectives.

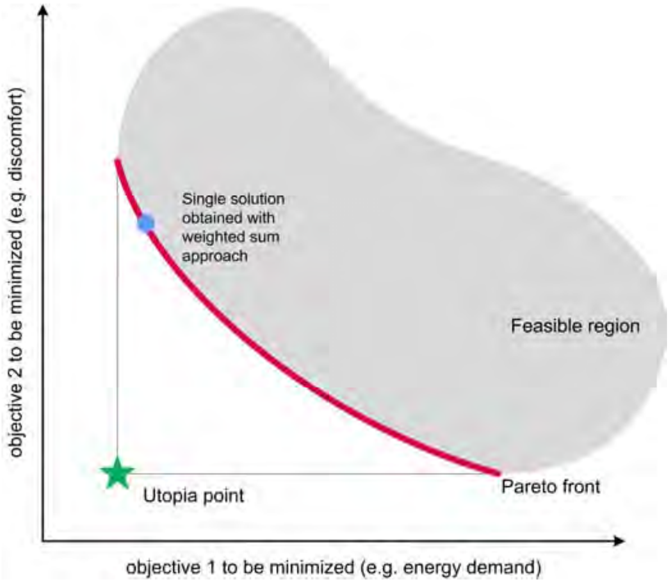

Figure 8: Visualization of the two-dimensional performance space with Pareto front.

Pareto optimization has recently been implemented with success as a design tool to support design of building envelopes (Hoes et al 2011; Palonen et al 2009; Tuhus-Dubrow and Krarti 2010; Wang, 2005). An extension of the application domain towards control of adaptive facades is however not yet explored.

The main asset of this true multi-objective approach is that the actual decision moment is delayed until all relevant information is available without relying on a priori knowledge. This increases understanding of balanced trade-off solutions for supporting every switching decision. One is able to ensure for instance that the result of optimization is close to the knee point, i.e. the solution that represents the fairest trade-off among all objectives, because all Pareto points are accessible. By having the chance to move along the Pareto line it also becomes possible to exploit willingness to allow high performance on one attribute to compensate for low performance on another. The added value of using Pareto optimization in adaptive architecture is best motivated with an example:

It follows from section –visual optimisation- that a large number of different facade configurations results in equally good visual performance, whilst having a range of unique appearances. This implies that within the subset of those best solutions there exists further optimization potential to improve on the other objectives. If weighting factors were predefined, the optimization search was only able to explore a small subset of good solutions. By using the proposed Pareto optimization however, we can effectively take advantage of this knowledge to move towards a better global optimum.

### *5.2 Simulation strategy*

The processing power of modern computers, used together with effective sampling methods facilitates performance evaluation of a large number of alternative façade adaptation scenario's. For each given combination of comfort needs and meteorological conditions, it is possible to find the set of façade parameters that best meets comfort requirements with the lowest amount of additional energy consumption. Such an intelligent parameter search is not driven by human preferences, but instead is able to explore the full option space of façade adaptation. The performance of each of the different options needs to be assessed in building performance simulation runs, and is then ranked accordingly on the basis of multiple objectives.

The relevant physical time constants in buildings (i.e. order of days) span across multiple periods of façade adaptation (i.e. order of minutes to hours). This fact prevents hopping from state to state and demands for including facade adaptation in dynamic simulations, to account for the effects of thermal inertia. To this end, we consider the building shell as a bounded subset of undefined solutions characterized by controllable variable values for the thermo physical and optical properties. Each change in adaptation should be made, based on the present state of the building, the future desired state of the building, disturbances in boundary conditions and the dynamic comfort constraints as presented in previous sections on thermal and visual comfort. Out of multiple options (trajectories) of façade adaptation an optimum needs to be found, by addressing the balance between multiple objectives. A model predictive control algorithm will be used for this purpose. The algorithm will be based on iterative, receding time-horizon, multi-objective optimization of the black-box building model. An online calculation will be used to explore state trajectories (dynamic behaviour) that emanate from the current state and find a control strategy for the specified time-slot that optimizes performance. This adaptation strategy will be implemented on a time-step basis. Each time-step in the simulation, these calculations will be updated and repeated, starting from the current state, yielding a new control and new predicted state path, thereby shifting the optimization horizon forward in time.

### *5.3 Challenges*

The task of implementing the presented integrated thermal and visual inverse modelling approach is currently being pursued in ongoing research activities. The remaining challenges in this endeavour are either (i) due to software limitations, or are (ii) directly rooted in the complex nature of the problem formulation.

*Software:* The existing building simulation programs were developed for the purpose of design, with only marginal attention for control issues. This is now the main reason that the number of features to model adaptive behaviour of façades is limited (Loonen, 2010b). On top of this, there is at present no single software tool available that is capable of predicting the simultaneous effects of thermal and visual comfort on the level of detail that is demanded by the program of requirements (Crawley et al, 2008). Coupling multiple building simulation programs in a co-simulation approach seems therefore inevitable. Issues related to the type and frequency of data exchange (Trcka, 2008) still need to be resolved for the present application. Implementation of the simulation strategy will take advantage of recent developments in the framework of the building controls virtual test bed (Wetter, 2010)

*Complexity*: The simulation strategy just outlined features a large number of degrees of freedom. The combination of many facade variables together with evaluations at multiple time-steps under uncertainty causes an exponential growth of the solution space. Effective measures are necessary in order to prevent the problem from becoming intractable. Even if we manage to keep control of this, we are still confronted with that fact that detailed building simulation with optimization in a model-based control approach is computationally expensive (Coffey et al., 2010). Striking the right balance between the ambition for truly optimal solutions and associated computation time becomes one of the significant challenges.

## 6 Conclusions and outlook

Thermal simulations show that the inverse modelling approach of FACET has a large energy saving potential, while maintaining a high level of comfort. The explorative simulations show, in comparison with a standard new Dutch office building (EPC value of 1,1), that a reduction of the cooling demand with a factor 3 and a heating demand with a factor of 6-10 is possible. Compared to a ‘passive house’ office the reduction factor is about a factor 2.

The method of superposition for visual optimization, with pre-processed Radiance output shows an effective way to enable evolutionary optimizations. The results provide feedback on the defined demands. There are many variants with similar performance output. The method will be extended with among other more working positions and light deflecting properties of the façade elements. In addition, full scale tests will be executed to get feedback on the user experience on FACET facades.

The FACET project is ongoing until end 2012 and by this time more results can be expected in terms of fully integral inverse modelling results for offices, schools and dwellings. Furthermore proof of concept for different adaptive building shell concepts and possible opportunities and potential for development of new technologies are expected. A big challenge will be to translate the theoretical, desired behaviour into ‘real world’ CABS concepts. The task of implementing the presented integrated thermal and visual inverse modelling approach is currently being pursued in ongoing research activities. The remaining challenges in this endeavour are either (i) due to software limitations, or are (ii) directly rooted in the complex nature of the problem formulation.

## 7 Acknowledgements

FACET is a Dutch EOS-LT R&D project, subsidised by Agentschap NL. Partners in the project are ECN, TUD, TU/e, CHRI and TNO. For more information please visit: www.eosfacet.nl

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