Climate adaptive building shells for the future – optimization with an inverse modelling approach

Bart de Boer & Gerrit Jan Ruijg
Energy reseach Centre of the Netherlands ECN
PO Box 1
1755ZG Petten
The Netherlands
b.deboer@ecn.nl

Roel Loonen, Marija Trčka & Jan Hensen
Eindhoven University of Technology
Unit Building Physics and Systems
P.O.Box 513
5600 MB Eindhoven
The Netherlands
r.c.g.m.loonen@tue.nl

Wim Kornaat
TNO PO Box 49
2600 AA Delft
The Netherlands
wim.kornaat@tno.nl

Keywords

energy savings, building shell, climate adaptive

Abstract

Most of currently designed and constructed building shells are fairly static systems which limits the possibilities for optimal energy performance and/or optimal indoor comfort. Solar shading is often only regulated by hand with (indoor) lamellas. This static behaviour of the shell often leads to discomfort and a high energy use for the various installations which are needed to climatise the building.

In common design practice energy performance calculation programs or, in the best case, dynamic building simulation programs are used as a tool to improve the building shell performance. Different options for façade constructions are compared to retrieve the best result in energy use. In the ongoing FACET project (Dutch acronym: 'Adaptive future façade technology for increased comfort and low energy use') a completely new, inverse modelling approach is chosen 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 design approach, a set of ideal, but realistic building shell parameters is computed for different climate conditions, at various time scales (seasons, day-night, instantaneous).

The 'ideal' adaptive behaviour makes it possible to maximize comfort and to minimize energy demand. Technologies to reach this 'ideal' behaviour are partly already available, in low or high tech solutions, such as smart glazing, variable vacuum insulation, insulating window covering, etc. However, further technology development is desired to fully meet the requirements.

This paper describes results of the inverse thermal modelling for a climate adaptive building shell. It shows that ideally adaptive building shells have the potential to practically eliminate the heat demand and to reduce the total heating and cooling demand by a factor 10, compared to state of the art new built offices under the Dutch climate. This is even a factor 2–3 lower compared to the very energy efficient passive house technology. The extremely low energy demand facilitates new technologies like compact heat/cold storages and the practical realisation of zero energy, or energy producing buildings in the near future.

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 condition-
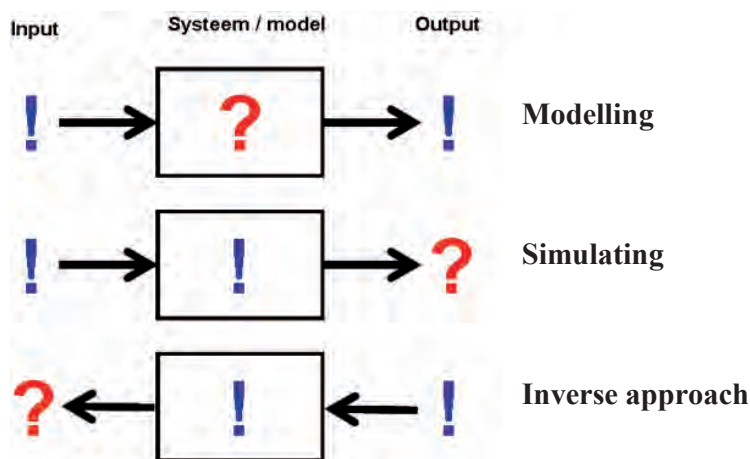
Contents   Keywords   Authors

Figure 1. Schematised representation of the inverse approach.

ing (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.

Climate adaptive building shells

Since the energy crisis in the early 70s 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. 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 'smart-facade', 'active facade', 'dynamic facade' and 'intelligent facade'.

In 2009, a simulation study on the inverse approach already indicated the large energy saving potential of CABS (Voorden, van der, et al 2009). In the FACET project in a first step the ideal adaptive behaviour of a building shell is sketched. In a second step in the project, CABS proof of concepts will be composed to meet the ideal requirements as much as possible.

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. 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 variable insulation (U), solar transmittance (G), solar shading and ventilation heat recovery) 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. 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 the results of the three taken steps in the process of thermal optimization will be given. In a first step the results of an explorative approach will be presented, in a second step the work on a dynamic simulation using an adaptive control strategy will be given and in a third (ongoing) step the future perspective of employing multi-objective optimization (MOO) techniques is presented.

Explorative inverse approach – FACET simulations in Excel

To determine the effect of dynamic shell properties an explorative study is performed where the energy balance of an office cell is evaluated with a 'pure' inverse approach in Excel. The

Contents   Keywords   Authors

idea is to vary the façade parameters (U-value, solar heat gain and ventilation factor) in timesteps of one hour. This is done in such a way that heating or cooling demand is eliminated as much as possible. In this approach the effect of the thermal mass of the building is essentially not taken into account. Furthermore it is assumed that the building shell will act as a black box filled with hypothetical material which can be either transparent or opaque and at the same time have a thermal conductivity which can be adapted to U values ranging from 0.1 to 10 W/m²K.

The energy balance of the office room is defined by:

$$E_{balance} = g\text{-value}*Q_{sol}+Q_{int} - (Vf*V*\rho cp+U*A)*(T_{comf}-T_{amb})$$

The aim is to minimise the energy balance for every hour of the year by optimizing the values of the three variables: solar gains (g-value), ventilaton rate (Vf) and insulation (U-value). In this case there is no heating or cooling necessary to meet the comfort temperature setpoint and the energy use is minimal. The variables can vary between the following values:

– Solar heat gain factor (g-value) between 0.06 (external shading closed) and 0.85 (external shading open).

– Ventilation factor Vf between 0.1 (Vf=2/h with 95 % heat recovery) and 5 (summer ventilation),

– U-value between 0.1 and 10 (R_c between 10 and 0.1)

Externally determined values are Q_{sol} and Q_{int}, which vary per hour. Q_{sol} is extracted from TRNSYS output, based on a weather file for Amsterdam. Q_{int} is 612 W if two persons are present, and otherwise 18 W after office hours. The volume of the office cell V is 52.5 m³, the interior capacitance ρc_p is 1,25 kJ/m³K, the facade surface A is 11.3 m².

The energy balance is one equation with three variables, which means there will not be one unique solution. To find optimal combinations of the variables, a certain priority is applied: in a standard setting it is desired to maximise the solar access and minimise the transmission and ventilation losses. If this leads to a heat excess, first the solar heat gains are limited and then there is a choice between increasing the conductivity (U-value) of the façade and increasing the ventilation rate. It is assumed that increasing the ventilation rate leads to a higher energy use than increasing the conductivity, so the latter is preferred. If variation of the three facade parameters does not lead to a heat balance equal to zero it can be concluded that in this time step there is a heating or cooling demand.

As can be seen in Figure 1, the shading is more often closed in summer than in winter, and in summer higher conductivity and ventilation rates are used for temperature regulation.

The resulting heating demand is 74 MJ/m², the resulting cooling demand is 18 MJ/m² per year. Changing the priority does not affect the heat and cooling demands. In comparison with an office building with an energy performance coefficient (EPC) of EPC=1,1 (which complies to a standard Dutch new building) a reduction of the cooling demand with a factor 3 is possible, and the heating demand shows a possible reduction factor of more than 6. Compared to the very low energy 'passive house' concept the reduction factor is about 2.

The frequency of occurrence of the different values of the façade parameters is depicted in Figure 4. Two bins are created for the extreme values, and one for the intermediate ones. It is clearly visible that the extreme values of the parameters occur more often than values in the intermediate bin. The maximum value of g occurs the most, about 60 % of the time, so the solar shading is most open. This is obvious at night time, but at day-

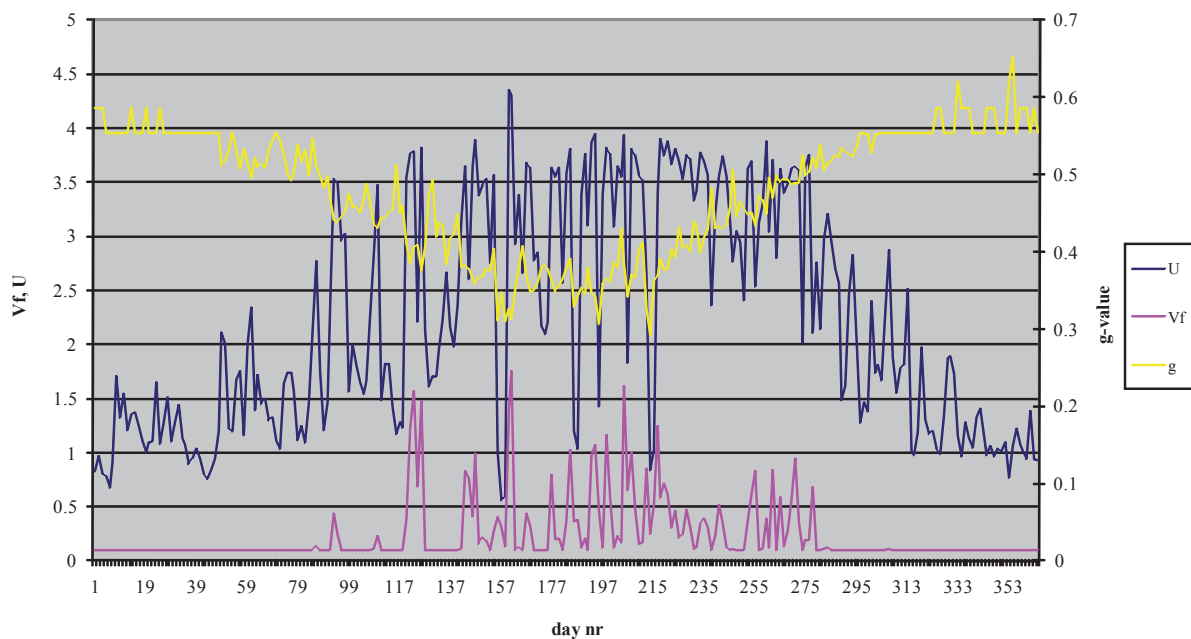**Workday average values of solar acces factor g, ventilationfactor Vf and heat conductivity U**

Figure 2. Working data average values for insulation (U), ventilaton rate (Vf) and solar heating gains (G); order for adaptive proportional control strategy: G, U, Vf.
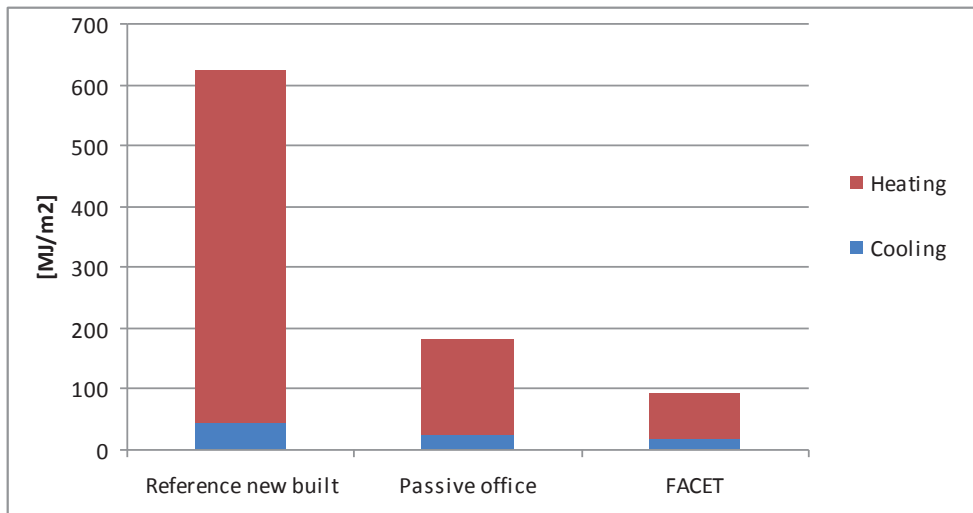
Figure 3. Heating and cooling demand at the reference office room, at 'passive house' office room and at a FACET office room.
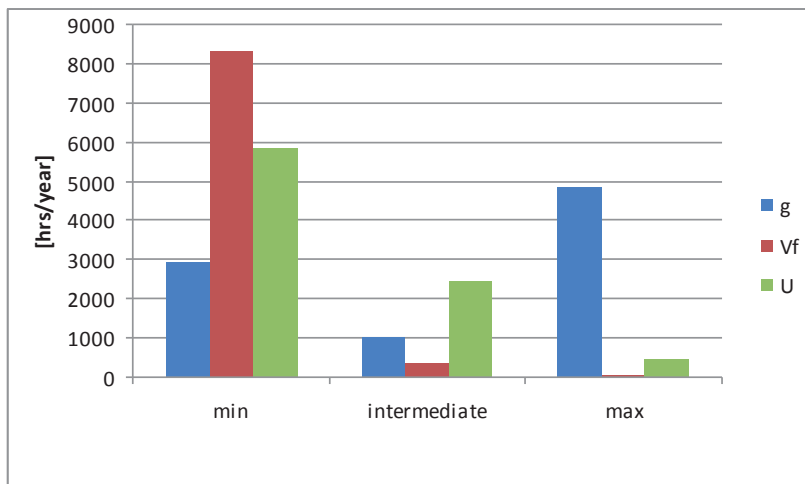

Figure 4. Frequency of occurrence of the different values of the façade parameters.

time they are mostly fully closed, 30 % of the time, so 10 % of the time the shading regulates the temperature.. For the heat conductivity and ventilation, the minimum values are the most abundant; the ventilation is at its minimum more than 90 % of the time.

Dynamic simulation using adaptive control strategy

In the rough previous analysis, the effects of internal building mass and outdoor temperature variations were not taken into consideration. Utilising the dynamics of the building offers an extra possibility for further energy performance improvement. In order to evaluate the effect of building dynamics on the energy performance, dynamic simulations have been performed using TRNSYS as simulation tool.

THERMAL COMFORT

The desired thermal comfort is based on the Dutch 'adaptive temperature gradient' (ISSO, 2004). The idea is that people adapt to higher or lower temperatures for example by the choice of their clothing. Also a more free running tempera-

ture, within determined boundaries, is regarded as being more comfortable. For the simulations this implies that the desired indoor temperature is not a fixed value but is related to temperatures of the past days, as illustrated in Figure 5. In this method a moving average ambient temperature is composed from the average temperatures of the past 4 days. Using this moving average ambient temperature for every day of the year an optimum comfort temperature is calculated as well as the temperatures at which 90 %, 80 % and 65 % of the people feel comfortable.

INVERSE MODELLING APPROACH

For the TRNSYS simulations the office room (at North and South orientation) was modelled, using an adaptive control mechanism, called 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 pos-
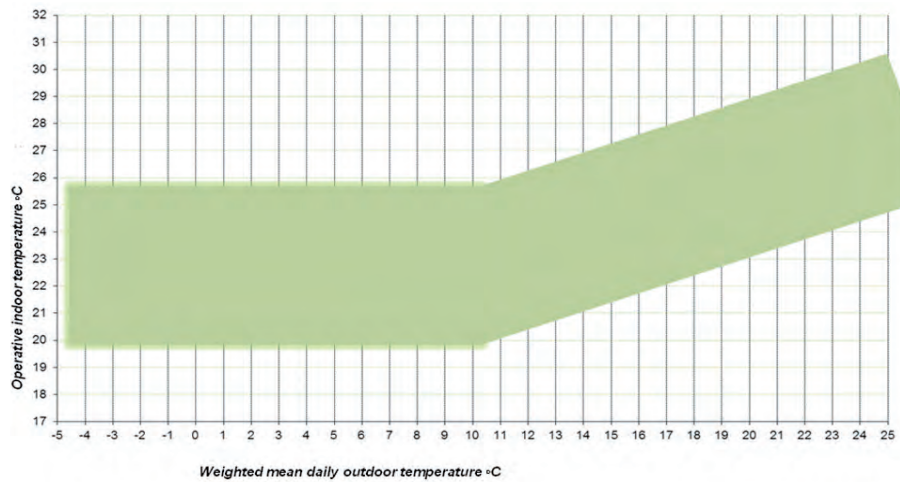
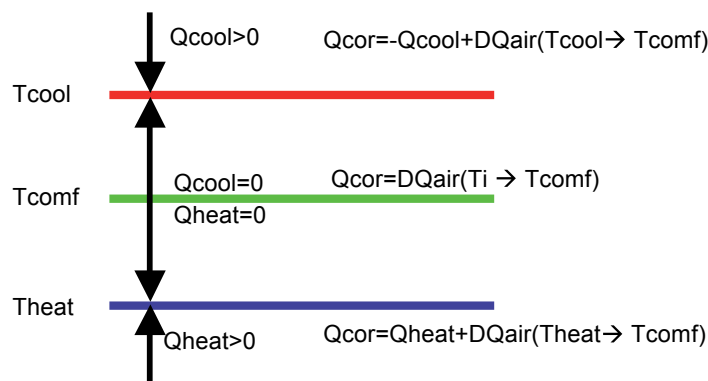*Figure 5. Thermal comfort: adaptive temperature gradient.*

Figure 6. Strategy of control mechanism for Qcor.

sible 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 resistance. So 11 different "window panes" are created with heat resistance ranging from 0.01 to 10, 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.

RESULTS

The TRNSYS simulation results are depicted in Figure 7. When simulated in TRNSYS the energy demand of the reference new built office turns out to be about 60 MJ/m2, what is a factor 10 lower than the result of the Excel exploration. It is expected that this is for the largest part due to the dynamic effect which allows temperature variations between the set temperatures of heating and cooling, and so uses thermal

storage in building mass to decrease the energy demand. But also the fact that TRNSYS takes more factors into account than the simple Excel explorative approach may play a role in this. The energy use of the FACET office is with 8 MJ/m2 a factor 8 lower than the reference office, what indicates that large energy savings appear possible compared to nowadays standards.

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 auxiliary energy consumption for changing the facade properties is not taken into account, because at this moment the actual design (and thus this energy comsumption) is not yet clear. Furthermore in both situations the energy of fans for the ventilation is not considered. Using natural ventilation gives further means for reducing the energy consumption.

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 multiobjective optimisation modelling method, as described in the next part of the paper.

Table 1. Range of variable and fixed façade properties.

	FACET office	**Reference office**
R_c (m^2.K)/W	0.01 <=> 10	4.6 m^2 HR^{++} glass (u=1.1 W/m^{2}K) 8.1 m^2 closed, R_c= 3 (m^2.K)/W
shading (-)	0 <=> 0.98[2]	0 or 0.9 (south)[1,2] 0 (north)
Heatrec. vent. (%)	0 <=> 95	70[3]
ventilation (dm^3/s)	winter 5 <=> 20 summer 5 <=> 80	28 (winter: 1.9 [1/h])[4] 35 (summer: 2.4 [1/h], +1K)[4] 36,5 (extra: 2.5 [1/h], +2K)[4]

Notes:
(1) During office hours shading in case solar load > 300W/m^2
(2) Maximum shading in both situations correspond to roughly the same fraction of light entrance.
Facet: (4.6+8.1) m^2 * 1 (g-value) * (1-0.98)= 0.254
Reference: 4.6 m^2 * 0.6 (g-value) * (1-0.9)= 0.276
(3) Only in combination with winter ventilation
(4) During office hours:
Winter ventilation in case indoor temperature < desired level+1
Summer ventilation in case indoor temperature >= desired level+1
Extra ventilation in case indoor temperature >= desired level+2
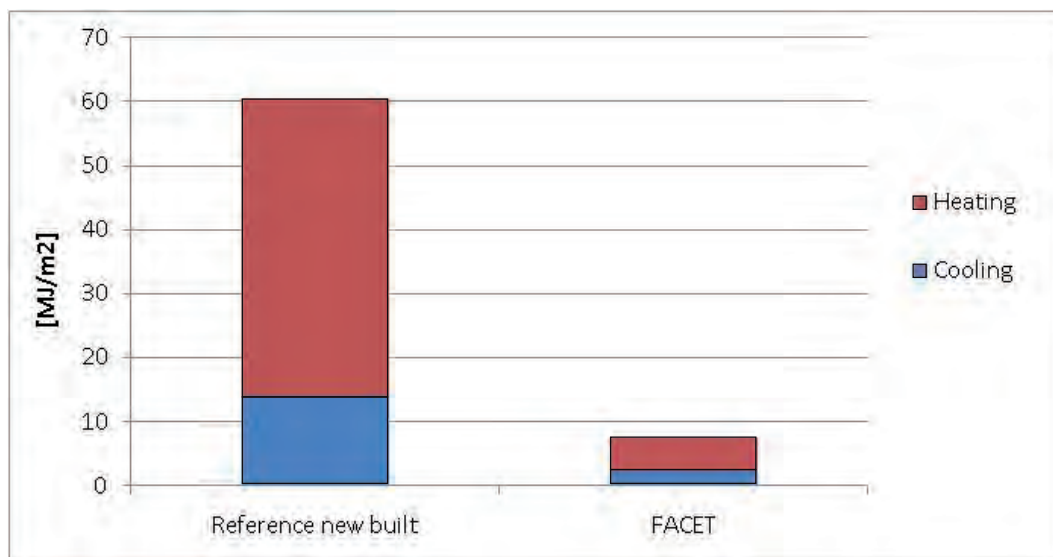Besides office hours: No ventilation

Figure 7. Heating and cooling demand of reference new built office and FACET office.

Future perspectives: multi objective optimisation

The results presented thus far are encouraging and confirm the hypothesis that it is worthwhile to continue directing efforts to design and development of adaptive façades. It can be argued however that the presented modelling approaches are not capable of disclosing the theoretical performance bound of adaptive building shell technology. The following limitations currently prevent the ultimate way of building envelope behaviour from being fully understood:

• The procedure for deciding on adaptive façade actions is driven by predefined priorities. This attribute introduces

a bias towards similar solutions under the wide variety of different conditions. In this way it restricts the number of attainable strategies to only a small subset of the potential option space.

• Another unfavourable characteristic of the tested approaches is that effects of different actions are investigated sequentially. Here we mean that one action is first executed to its full extent before continuing to the next action. This consecutive approach misses the opportunity to map how simultaneous partial actions might mutually enhance each other.
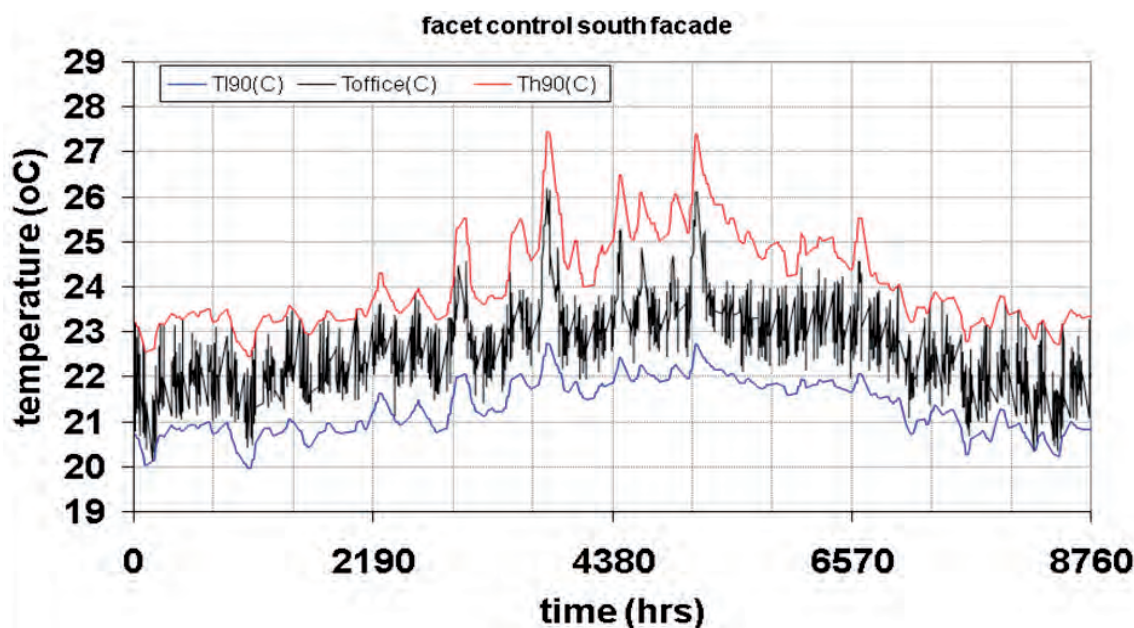
Contents   Keywords   Authors

Figure 8. Indoor temperature 99,5% within '90% satisfactory' boundaries of adaptive temperature gradient.

- A third key limitation of the existing approaches is the fact that decisions are only based on current information on disturbances and events that happened in the past. By introducing a control strategy with the capacity to take advantage of expected future changes, we hope to bring the feasible potential of CABS to a higher level.

In this section we propose an alternative method that will be used in our search for the optimal behaviour of dynamic façades. This strategy relies on three principles: exploration, optimization and anticipation. The remainder of this paper introduces these three principles, elaborates more on the envisioned simulation strategy, and finally discusses some of the challenges that need to be resolved in this ongoing research effort.

EXPLORATION

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 the requirements with the lowest amount of energy consumption.

Such a 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 is assessed by building performance simulation runs, and then ranked accordingly. This method overcomes the issues concerned with priorities and sequential actions, and therefore drastically enlarges the searched space. In turn, this increases the chances of arriving at the overall best solution.

OPTIMIZATION

The multiple functions of the building shell are typically diverse and sometimes even competitive in nature. Harmonizing these performance requirements in a good way therefore remains a challenge in both static and adaptive building designs. The use

of optimization methods however can help in accomplishing this task by converging the parameter search towards the best solutions. Traditional single objective methods, possibly augmented with constraints or a weighted-sum approach for trading-off multiple criteria, have demonstrated to not always bring satisfactory results (Das and Dennis (1997); Mourelatos and Liang (2006)).

We aim to overcome this deficiency by employing multi-objective optimization (MOO) techniques as a tool for enabling well-informed decision making (Hopfe, 2009). The main asset of this 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. Application of MOO is not limited to the bi-objective compromise between energy demand and thermal comfort only. We foresee the incorporation of visual comfort considerations as viable future extension.

MOO can be used to assist short-term decisions in control of CABS, but is also helpful to visualize the performance benefits of CABS on an annual basis. We contend that the performance of a well-designed and well-controlled CABS can go beyond the Pareto set of a static design and move in the direction of the utopia point (Figure 9).

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 latter instant" (Rosen, 1985). Buildings do not react instantaneously to changes in their environment; the thermal characteristics of the structure and shell introduce delay and a damping effect. If adaptive building shells were competent of basing their state transitions on forward-looking, this would open up several of the established advantages pertaining to building-related model predictive control, including:

Contents   Keywords   Authors
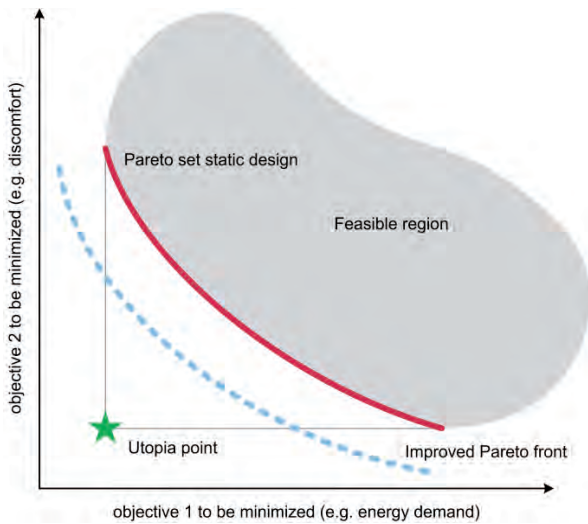
(adapted from (Olewnik et al., 2004))

Figure 9. The improved Pareto set of CABS can surpass performance of a conventional façade.

- Making smart use of variable thermal mass to attenuate or shift peak loads and keep temperature fluctuations within the comfortable range (Hoes et al., 2011).

- Exploiting knowledge about periodicity of occupancy and load patterns to maximize the benefits of on/off behaviour and start-stop times (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 (Oldewurtel et al., 2010; Zavala et al., 2009).

Apart from these applications, anticipation can also 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.
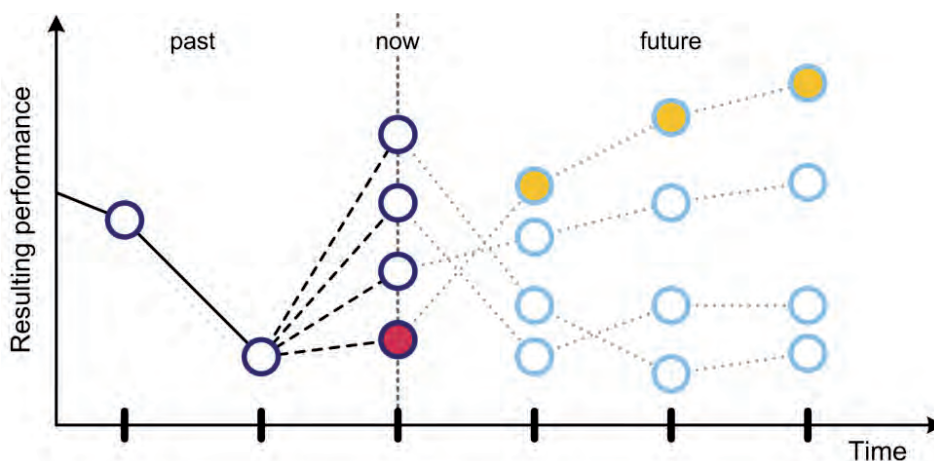
The reward of introducing proactive control primarily rests on the quality and validity of predictions. Highest potential benefits are expected in 'heavy' buildings, and for supporting supervisory control decisions with multiple complementary servicing actions involved. However, ss the forecast horizon increases, the predictions are becoming increasingly uncertain (Zavala et al., 2009). It is important to be aware of this and the fact that predictions can potentially be wrong. The performance robustness of selected strategies should therefore be a point of attention. In addition, a trade-off has to be made between the length of the forecast horizon and corresponding computational cost.

SIMULATION STRATEGY

The relevant physical time constants in buildings (i.e. order of days) span across multiple periods of façade adaptation (i.e. minutes to hours). Including adaptation in dynamic simulations is thus necessary 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. This process is not about enhancing the performance of proposed or existing designs but instead aims at determining what transient adaptive thermo physical and optical characteristics a façade ideally should exhibit.

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 dynamic comfort constraints. 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, these calculations will be updated and repeated, starting from the

(adapted from Bosman and La Poutré (2007))

Figure 10. Why anticipation is useful.

current state, yielding a new control and new predicted state path, thereby shifting the optimization horizon forward in time.

CHALLENGES

The task of implementing the presented 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.

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). Specific enhancements are required to allow for simulation of the variability of thermal mass. The current tools do moreover not offer the capabilities to facilitate the advanced decision making procedure with forward looking. Coupling building simulation to a more generic software platform (e.g. Matlab) in a co-simulation approach seems therefore inevitable. Issues related to the type and frequency of data exchange (Trcka, 2009) still need to be resolved for the present application.

The simulation strategy just outlined features a large number of degrees of freedom. The combination of many 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 predictive controllers 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.

The 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 questions what optimal performance actually might be in terms of comfort, we realize that it is important to also focus on the maximum acceptable rate-of-change (Kim and Kim, 2007).

Conclusions, remarks and outlook

Both the Excel and dynamic simulations show that the inverse modelling approach of FACET has a large energy saving potential. 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.

Simulations show that reduction of the solar heating gains (g-value) is the main factor to maintain the temperature in a building close to the desired maximum value. Increase of heat conductivity and ventilation (bypass or natural) perform comparably well as instruments to decrease the cooling demand in summer as long as the ambient temperature is lower than the inside temperature. In the present control strategy

in Excel and TRNSYS the extreme values of the facade parameters occur most frequently. 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.

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.

References

Bosman, P. and La Poutré, H. (2007) "Learning and Anticipation in Online Dynamic Optimization with Evolutionary Algorithms: The Stochastic Case", in *Proceedings of Genetic and Evolutionary Computation Conference - GECCO-2007,* London, UK.

Coffey, B., Haghighat, F., Morofsky, E. and Kutrowski, E. (2010) "A software framework for model predictive control with GenOpt". *Energy and Buildings* 42(7): 1084-1092.

Das, I. and Dennis, J. (1997) "A closer look at drawbacks of minimizing weighted sums of objectives for Pareto set generation in multicriteria optimization problems", *Structural and multidisciplinary optimization* 14(1): 63-69.

Davies, M. (1981), "A wall for all seasons", *RIBA Journal* 88(2): 55–57.

Haartsen, J. and Brouwer, J. and Mihl, H. (1999) "De intelligente gevel" Delft University Press.

Hoes, P., Trcka, M. and Hensen, J. (2011) "Investigating the potential of a novel low-energy house concept with hybrid adaptable thermal storage", *Energy Conversion and Management,* Accepted for publication.

Hopfe, C. (2009) *Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization*, PhD-Thesis, Eindhoven University of Technology.

ISSO 2004. Publicatie 74: Thermische behaaglijkheid - eisen voor de binnentemperatuur in gebouwen. Rotterdam: Stichting ISSO, Kennisinstituut voor de installatiesector.

Kim, S.Y. and Kim, J.J. (2007) "Influence of light fluctuation on occupant visual perception", *Building and Environment* 42(8): 2888-2899.

Loonen, R. (2010a) *Overview of 100 Climate Adaptive Building Shells*, part of MSc-Thesis: 'Climate Adaptive Building Shells – What can we simulate?', Eindhoven University of Technology.

Loonen, R. (2010b) *Climate adaptive building shells – What can we simulate?*. MSc-Thesis, Eindhoven University of Technology.

Mourelatos, Z. and Liang, J. (2006) "A Methodology for Trading-off Performance and Robustness Under Uncertainty", *Journal of mechanical design* 184(4): 856-863.

Oldewurtel, F., Gyalistras, D., Gwerder, M., Jones, C., Parisio, A., Stauch, V., Lehmann, B. and Morari, M. (2010)

Contents   **Keywords**   **Authors**

"Increasing energy efficiency in building climate control using weather forecasts and Model Predictive Control", in *Proceedings of the 10th REHVA World Congress Clima 2010,* Antalya, Turkey.

Olewnik, A., Brauen, T., Ferguson, S. and Lewis, K. (2004) "A Framework for Flexible Systems and Its implementation in Multiattribute Decision Making". *Journal of Mechanical Design* 126(3): 412-419.

Rosen, R. (1985) *Anticipatory systems,* p:341, New York: Pergamon Press.

Trcka, M. (2008) *Co-simulation for performance prediction of innovative integrated mechanical energy systems in buildings,* PhD-Thesis, Eindhoven University of Technology.

Voorden, M. van der , de Wilde, P. de Boer, B, and Bakker, L. (2009), "Climate Adaptive Building Shells" *TVVL Magazine* 3/2009

Zavala, V., Constantinescu, E., Krause, T. and Anitescu, M. (2009) "On-line economic optimization of energy systems using weather forecast information". *Journal of Process Control* 19(10): 1725-1736.

Acknowledgements

Contents Keywords Authors