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The impact of an ideal dynamic building envelope on the energy performance of low energy office buildings

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Abstract

This paper shows the results of a research activity aimed at assessing the advantages of an ideal adaptive building skin over conventional building envelope systems.
The basic idea underlying the research consists in imagining an ideal building envelope system characterised by the capability of continuously changing (within a certain range) some of its thermo-physical and optical properties. The reason for the continuous tuning of thermo-physical and optical properties lies in the assumption that an optimised (fixed) configuration, where the properties do not change over time, is not able to minimise the total energy demand of the building at each moment.
For the sake of this purpose, an ideal dynamic WWR (Window-to-Wall Ratio) building envelope system for low energy office buildings was modelled and simulated. An integrated, commercial thermal-lighting building simulation tool (*EnergyPlus*) was used to perform the calculation. The energy performance of such a system was then analysed and compared against the performance of a conventional façade realised with best-available technologies.
The results of the investigation demonstrated the advantages of a dynamic WWR configuration over a static one. However, the improvements achieved in energy demand were lower than expected. This behaviour is strictly related to the configuration of the building used as a reference, which already showed a very high energy performance.
Limitations presented by the research method are also briefly pointed out and discussed.

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Keywords: Responsive Building Components; ideal building skin; façade; dynamic systems; low energy office buildings; numerical simulation.

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Nomenclature

E	Normalized annual energy demand
WWR	Window- to-Wall ratio

Greek symbols

Δ%	Percent reduction of primary total energy demand

Subscripts

I – XII	Referred to the n^{th} month (I: January, II: February, … XII: December)
H	Referred to the hourly time-step
M	Referred to the monthly time-step
W	Referred to the weekly time-step
Y	Referred to the annual time-step

1. Introduction

Due to the significant impact of the building sector on greenhouse gas emissions, newer and stricter regulations aimed at reducing total energy use in buildings have appeared in the last few years. In the European context, all the new constructions will thus soon be asked to be nearly Zero Energy Buildings (nZEB) [1]. In order to reach this target, new concepts and technologies capable of further improving buildings' energy efficiency need to be developed.

In this context, a very promising strategy to overcome current technology limitations is represented by a non-conventional approach that considers the building a responsive and dynamic system – and not a static object. The building skin is probably the element of the construction which shows, according to this vision, the largest potential, especially if its properties can be continuously tuned so that the best response to different dynamic indoor and outdoor boundary conditions can be achieved. Even though it cannot be stated that a dynamic building envelope alone could represent the solution to achieving the nZEB target, great expectations are placed on advanced dynamic façade systems.

While it is possible to find in the literature analyses of energy and comfort improvements given by single dynamic building envelope technologies, a more general analysis on the theoretical limits of what can be achieved by a dynamic and responsive envelope over a conventional system is a much less common investigation.

Considering the relevant influence of the glazed surface on the energy balance of buildings (glazing systems allow a much higher interaction with solar radiation than opaque components), and the potential demonstrated by previous analyses [2], the performance of an ideal system able to modify the WWR (Window-to-Wall Ratio) of the façade is herewith evaluated. Opaque and transparent surfaces (the latter, with or without a shading system) greatly differ in thermal and optical properties – not only as far as the modulation of the solar energy transmission is concerned, but also for what concerns thermal resistance, thermal inertia and daylight exploitation. Even though a system that presents a dynamic WWR is nowadays not yet available in practice, the implications of such a system can still be evaluated by means of mathematical modelling and numerical simulations.

Therefore, the aim of this investigation is to evaluate in a qualitative/quantitative way the advantages given by a dynamic building envelope system over a conventional one, using the WWR as a case study. The significance of this analysis is supported by a recent investigation [3] where the WWR was identified as one of the most (and for many aspects the most) important parameters in façade design, with deep implications on the total energy demand.

The modelled system is hence an ideal building envelope whose main characteristic is the ability to change its WWR and its correspondent thermo-physical properties during the year, with the aim of minimising the annual total primary energy demand of the building. In this paper, the performance of such an ideal dynamic building skin is compared against that of a fix WWR system, in case of a Nordic climate (Oslo).

2. Methodology

2.1. Integrated thermal-lighting simulations

The evaluation of the performance of a dynamic WWR system originates from the outcomes of a series of analyses [4,5] in which the search for the optimal WWR (i.e. the WWR that minimises the annual total energy demand) was carried out on a yearly basis. The primary total energy demand, E_{tot}, was calculated for an office building by means of numerical simulation for the entire year. Simulations were carried out with *EnergyPlus 7.0*. and a sub-hourly time-step (15 minutes) was used.

The simulated building has a common layout – bar shape, corridor in the middle of the floor, offices facing the two main, opposite façades, with staircases and services at the two ends of the corridors. The Surface over Volume Ratio of the building is 0.25 m^{-1}. Building equipment is air-to-air heat pump for both cooling and heating, with SCOP of 2.6 and 3.8, for heating and cooling season respectively.

The full list of materials and the thermo-physical properties used in the dynamic WWR ideal building skin are the same as those of the single skin building envelope presented in [4]. The main properties of the façade components are resumed in Table 1.

Table 1. Properties of the components of the façade module used in the simulations.

Technology	Property		Unit
Opaque sandwich panel	*U-value*	0.15	[$W\ m^{-2}\ K^{-1}$]
Glazing (triple glass pane)	*U-value*	0.70	[$W\ m^{-2}\ K^{-1}$]
	SHGC	0.46	[-]
	τ_L	0.53	[$kW\ h_{pe}\ m^{-2}$]
Shading (external venetian blind)	ρ_E	0.80	[-]
Frame (aluminum, thermal break)	*U-value*	1.00	[$W\ m^{-2}\ K^{-1}$]

2.2. Data post-processing and determination of the dynamic WWR performance

The annual primary total energy demands were calculated for five different fixed WWR configurations (WWR = 0.20; 0.35; 0.50; 0.65; 0.80), according to the specification presented in the above section. After that, by means of a cubic spline interpolation, the discontinuous function defined for the five different WWRs was transformed into a continuous function which returned an estimated value of the annual total energy demand correspondent to each WWR in the range 0.20 ÷ 0.80 (Eq. 1). Spline interpolation was carried out with the dedicated function available in the *MatLab* environment, based on a cubic equation to interpolate between two knots. The function was assured to be continuous and differentiable in the entire domain (including the five knots), by using not-a-knot conditions at the two extremes of the range. The optimal WWR that minimised the annual energy demand was found in relation to the absolute minimum of this function.

$$ {}_Y E_{tot} = spline\left({}_Y E_{tot}(0.20), {}_Y E_{tot}(0.35), {}_Y E_{tot}(0.50), {}_Y E_{tot}(0.65), {}_Y E_{tot}(0.80) \right) \quad (1) $$

Since within the same month, week or even day, the boundary conditions may change considerably, the optimal WWR calculated with the above-mentioned procedure is not the WWR that minimises the energy demand at each time-step (month, week, day, hour). For example, the WWR that minimises E_{tot} in January is very likely to be different from the one that minimises E_{tot} in June, or in Week 50, or the annual energy demand. It is hence possible to imagine that, if a façade were able to continuously change its WWR in order to meet the minimum energy demand at each time-step – the duration of the time-step is worthy of investigation – considerable improvement could be reached and further reduction in energy demand could be achieved.

If a dynamic WWR façade were conceived, the best annual performance would be reached when the façade adopted the most favourable configuration in each time-step (e.g. a month). Thus, the annual total energy demand, ${}_{Y}E_{tot}$, would be given by the sum of the minimum values of the 12 monthly energy demands, ${}_{M}E_{tot}$ (Eq. 2).

$$ {}_{Y}E_{tot}(dynamic) = \sum_{M=1}^{XII} \min\left({}_{M}E_{tot}(WWR)\right) \qquad (2) $$

2.3. Remarks about the adopted procedures for dynamic WWR performance calculation

As mentioned, simulations were carried out by means of the *EnergyPlus* code with a fixed value of WWR. During the data post-processing phase, spline interpolation was applied to monthly (or shorter) total energy demands obtained from different simulations (with different WWRs) and the minimum energy demands were then summed to obtain the performance of the dynamic WWR façade.

This procedure implies that energy demands that are obtained from different simulation sets can be summed. This is true if the values of the physical quantities in a certain time-step do not significantly affect the values of the same physical quantities in the following time-step, hence that the inertial and transient effects within the building have negligible or little influence on the energy performance of the building.

It cannot be assured that a succession of optimal sets of values (i.e. the sets that maximize the energy performance at each time-step) give the lowest possible total energy demand over a certain period. In other words, it cannot be ensured that the set of values that minimises the energy demand at a certain time step t provides, for the next time step (t+1), boundary conditions such that the absolute minimum in that time step (t+1) can be reached too.

In fact, if the building energy balance is achieved by imposing a heat capacity of the system at zero (or neglected), the sum of the different monthly energy demands is fully acceptable – this is one of the basic assumptions behind the monthly quasi-steady-state calculation methods of building energy performance presented in the International Standard ISO EN 13790 [6]. Even though it is probably correct to affirm that the transient effects from month to month have limited influence on the monthly energy performance, and thus the above-mentioned procedure provides trustworthy results, the question whether the method is or is not fully reliable when shorter time ranges are selected (e.g. weekly, daily, or even hourly WWR) is unanswered.

Because of this limitation, the aim of this investigation was not to quantify the energy savings given by a dynamic WWR system, but to highlight the trends towards a better energy performance when a dynamic system is used and when shorter ranges of dynamicity are employed. Therefore, the analysis of performance of the dynamic WWR system with a shorter time-step (notably one week, one day, one hour), was conducted regardless of the above-mentioned limitation. Nevertheless, the approximation introduced when the time step becomes smaller may be quite relevant and the full trustworthiness of the results may be questionable.

2.4. Comparison between static and dynamic WWR

Simulations and data post-processing was carried out for the different locations, but only the results related to Oslo are herewith presented due to the lack of space. Results of dynamic WWR concept were compared with the results obtained with a standard system (static WWR) presented in [4,5]. The main four orientations were simulated for the selected location.

The assessment of the reduction in primary total energy given by a dynamic WWR façade over a fixed static WWR façade was evaluated according to Eq. 3.

$$ \Delta\% = 100 \cdot \frac{{}_{Y}E_{tot}(dynamic) - {}_{Y}E_{tot}(fix)}{{}_{Y}E_{tot}(fix)} \qquad (3) $$

3. Results

The advantages of a dynamic WWR configuration are demonstrated by the outcomes of the investigation. In Fig. 1, the percentage reductions are plotted for different time-steps and façade orientations in the case of an office building located in Oslo (humid continental climate). The full data set of energy demand for both static and dynamic configurations is reported in Table 2.

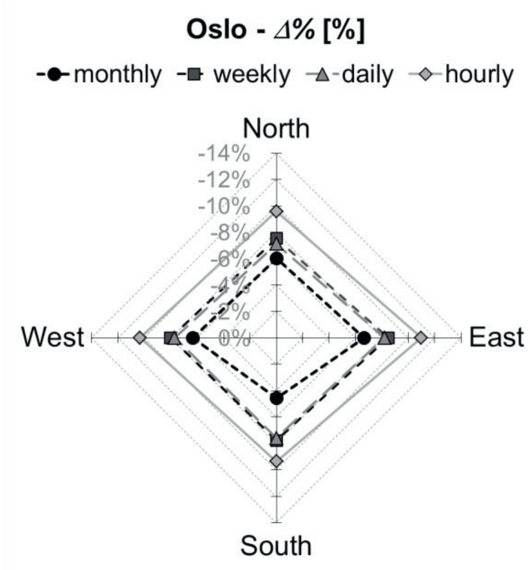

Fig. 1. Percentage reduction of the primary total energy demand by means of a dynamic building skin for different orientations and dynamic WWR time-steps for a building located in Oslo.

Table 2. Comparison of the annual energy performance of a building located in Oslo with static and dynamic WWR building skin.

Technology	Time-step	Quantity	Unit	Façade orientation			
				South	North	East	West
Static WWR	annual	Optimal WWR	[-]	0.57	0.41	0.41	0.42
		${}_{Y}E_{tot}$	[kW h_{pe} m^{-2}]	41.8	50.7	50.7	50.5
Dynamic WWR	monthly	$\Sigma_{M}E_{tot}$	[kW h_{pe} m^{-2}]	39.9	47.6	47.3	47.3
	weekly	$\Sigma_{W}E_{tot}$	[kW h_{pe} m^{-2}]	38.6	46.9	46.4	46.4
	daily	$\Sigma_{D}E_{tot}$	[kW h_{pe} m^{-2}]	38.7	47.1	46.5	46.6
	hourly	$\Sigma_{H}E_{tot}$	[kW h_{pe} m^{-2}]	37.9	45.8	45.1	45.3

Examples of plot that show how the optimal WWRs changes along the time, for monthly and weekly dynamics time-step, are shown in Fig. 2 (for south- and east-exposed façades).

As shown in Fig. 1, a dynamic WWR configuration with a monthly time-step gave an average energy demand reduction of about 6%. However, with the time-step getting shorter (weekly and daily), the advantages given by the dynamic configurations did not grow with the same intensity. Moreover, there was no difference in energy performance between the weekly and the daily dynamic WWR configuration, but the energy performance of the weekly dynamic configuration was even slightly better than that of the daily dynamic configuration. This unexpected result can be due to the above-mentioned limitations of the research method when the time-step gets shorter and shorter and requires further investigations.

The east-exposed façade was where dynamic configurations gave a better performance, followed in the ranking by west- and north-exposed façades; south-exposed façades showed the lowest energy demand reduction when a dynamic WWR system was employed. However, it must be stated that this difference in performance of the façades as a function of the orientation are marginal and could easily be within margins of the calculation method.

To summarise, the following comments can be given for the analysed location:

- a significant increase in efficiency could be achieved passing from a static configuration to a dynamic WWR skin with monthly time-step – this is probably due to the peculiarity of the climate that can present very high heating demand in winter but shows overheating phenomena in summer;
- weekly or daily dynamic WWR were not able to provide a significant advantage with respect to a dynamic WWR with monthly time-step. Within the same week, the optimal WWR configuration does not probably change considerably from day to day, and thus the optimal WWR during an entire week is a sufficiently good average of the optimal WWR configurations during the seven days of the week;
- in case of hourly dynamic WWR, i.e. when the dynamicity of solar radiation plays a relevant role, the adaptive skin further improved the performance of the building.

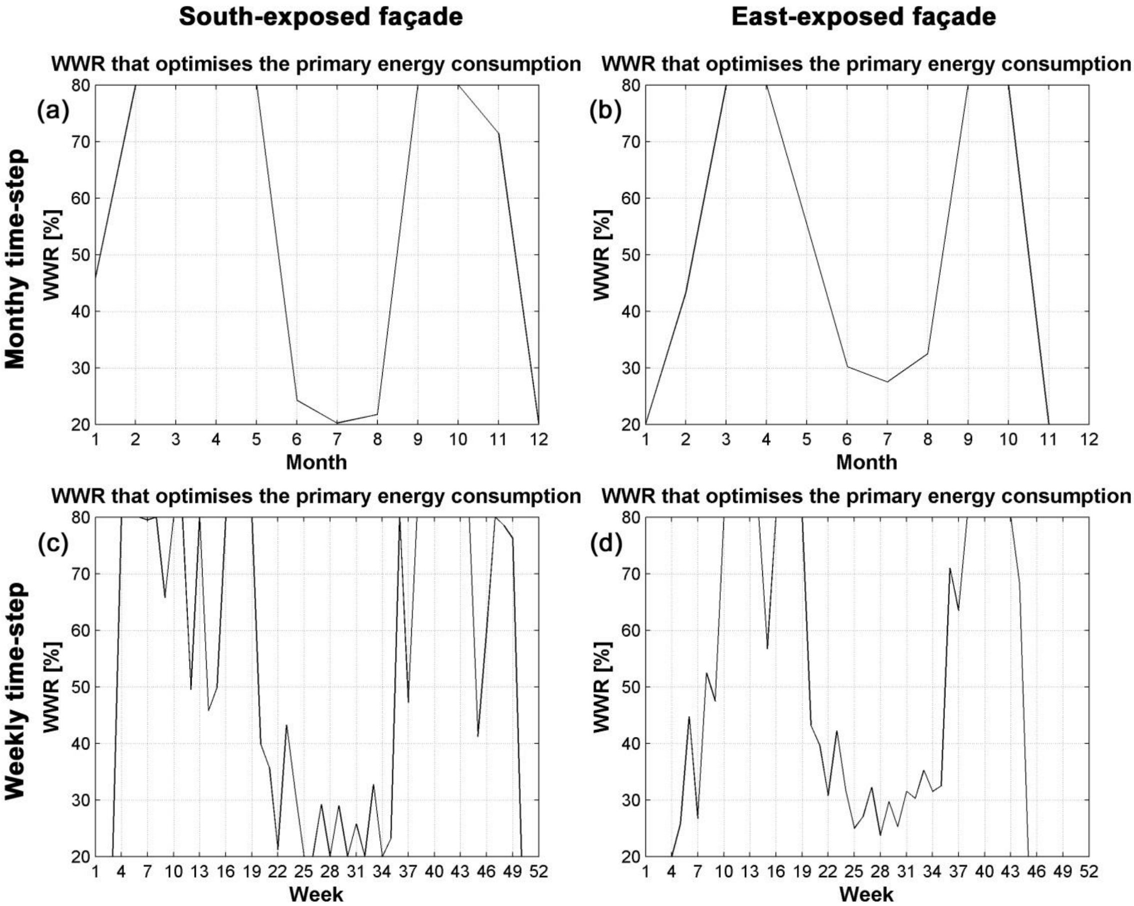

Fig. 2. Optimal WWRs for monthly optimisation (a, b) and weekly optimisation (c, d) for south-exposed (a, c) and east-exposed (b, d) façades.

4. Discussion

In order to fully evaluate and explain the results of this analysis, it is worth highlighting the some assumptions and conditions that are at the basis of this research.

This investigation refers to an office building, which is characterised by a set of internal boundary conditions and occupancy schedules that usually differ considerably from other types of buildings such as dwellings. The same analysis for other types of buildings may lead to different results based on the different internal heat gains and daylighting exploitation and it might reveal higher influence (and potentials) in the use of dynamic envelope systems. In fact, as revealed in previous analyses focusing on conventional façade systems in office buildings [4,5], the impact of the WWR configuration in the total energy demand is quite moderate, thought this parameter is probably, in the building envelope context, the one that affects the most the energy performance. This behavior is very common in case of an optimized building, where the impact of each sub-system on the entire building performance becomes less relevant.

In this perspective, it should not be very surprising that the advantages given by the dynamic WWR over the fix WWR is quite constant, regardless of the orientation. In fact, the fix WWR configuration used as a reference is already a solution with a high performance and with some degree of dynamics – i.e. the fix WWR configuration has shading devices whose displacement has been already optimized, cf. [4].

Secondly, the methodology adopted in the analysis presents some limitations, especially as far as short dynamic time-steps are concerned. Improvement in the above mentioned methodology could be achieved by giving time-continuity to the simulations with different WWR, so that the temperature field conditions at the end of time step t in the simulation would be the initial conditions for the simulation time-step $t+1$. Such a procedure could be achieved combining *MatLab* and *EnergyPlus* by means of existing toolboxes for co-simulation (e.g. MLE+, [7]). In this case, even the results coming from simulations with short dynamic time-steps would be fully significant and would probably result in a much higher impact of the dynamic WWR ideal system.

Finally, in this paper only the results for a Nordic climate setting are shown for the sake of brevity. Analyses concerning other climates have also been carried out the framework of this research activity and give similar results to that presented in this paper. As a more general comment, it is possible to state that buildings located in more balanced climates (not hot- or cold-dominated) show an even better improvement in energy performance if a dynamic WWR system is adopted. On the contrary, dynamic WWR systems in buildings located in hot-dominated climates shows very little advantages over a fix WWR configuration. However, this somehow surprising outcome can be again related to the adopted methodology and the reference fix WWR technology, and would probably result in a different picture if short time-step analysis could be fully trustworthy – in case of hot-dominated climates, the dynamics of solar radiation, characterized by very short time-steps, becomes even more important and a dynamic system needs to be able to change its status within a relatively short time interval.

5. Conclusions

In the present paper, an ideal dynamic WWR technology was conceptualised and its performance was assessed by means of available simulation tools (*EnergyPlus*) and a dedicated data post-processing technique. Limitations presented by this method were pointed out and discussed.

The results of the investigation demonstrated the advantages of a dynamic WWR configuration over a static one, even though the improvements achieved in energy demand were lower than expected. This behaviour is related to the configuration of the building used as a reference, which already showed a very high energy performance. This outcome is in accordance with the so-called "law of diminishing returns" [8], stating that improvements in case of very advanced technologies are very complicated and expensive. A more foreseeable outcome was instead revealed as far as the influence of the dynamic property time-step; the shorter time-step with which the WWR configuration can change, the larger the improvement in energy efficiency. However, non-linear behaviour was recorded as far as this aspect is concerned.

The south-exposed façade did not have the highest improvement in energy efficiency (a quite unexpected result, which can again be correlated to some of the assumptions in the methodology and in the fix WWR configuration used in the comparison). There seems to be no specific orientation where the advantages are more relevant than in the others.

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