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Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight

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Abstract

The façade design is and should be considered a central issue in the design of energy-efficient buildings. That is why dynamic façade components are increasingly used to adapt to both internal and external impacts, and to cope with a reduction in energy consumption and an increase in occupant comfort. To gain a complete picture of any façade's performance and subsequently carry out a reasonable benchmarking of various façade alternatives, the total energy consumption and indoor environment need to be considered simultaneously. We quantified the potential of dynamic solar shading façade components by using integrated simulations that took energy demand, the indoor air quality, the amount of daylight available, and visual comfort into consideration. Three types of façades were investigated (without solar shading, with fixed solar shading, and with dynamic solar shading), and we simulated them with various window heights and orientations. Their performance was evaluated on the basis of the building's total energy demand, its energy demand for heating, cooling and lighting, and also its daylight factors. Simulation results comparing the three façade alternatives show potential for significant energy reduction, but greater differences and conflicting tendencies were revealed when the energy needed for heating, cooling and artificial lighting were considered separately. Moreover, the use of dynamic solar shading dramatically improved the amount of daylight available compared to fixed solar shading, which emphasises the need for dynamic and integrated simulations early in the design process to facilitate informed design decisions about the façade.

Keywords: Dynamic solar shading; Integrated simulation; Energy demand; Indoor environment; Office buildings

1. Introduction

The ever-increasing focus on the environment and climate transformation as a consequence of the emission of greenhouse gasses means that the building industry is facing a new reality (IPCC, 2008; Brundtland, 1987). Energy consumption doubled in the period 1971–2007, and the operation of buildings accounts for 40% of the overall energy consumption (International Energy Agency, 2009). The Energy Performance of Buildings Directive (EPBD, 2002) has become an important part of the new reality, and with the recent political acceptance of the new version that prescribes that all new buildings must be "nearly zero-energy buildings" by 2020 (EPBD, 2010), energy efficiency at every level within the built environment has simply become a prerequisite.

The overall reason for constructing buildings is to shield occupants from the outdoor environment and obtain a certain level of indoor comfort. Consequently, to a great extent, it is the level of occupant comfort that determines how much energy is used to operate the building. This puts the façade, as the actual separator between the indoor and outdoor climate, at the centre of the "energy reduction issue". Choosing the optimal façade, however, is a complex

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discipline with many, often contradictory, parameters of considerable interdependence (Ochoa and Capeluto, 2009).

The introduction of dynamic fenestration creates the possibility of obtaining a more beneficial utilisation of the available resources, such as insolation and daylight, with respect to both energy demand requirements and occupant comfort (Lee et al., 1998). There has been previous research into dynamic fenestration technologies to determine their significance in relation to energy consumption and occupant comfort. Results show the potential of dynamic fenestration components, ranging from a decrease in cooling and lighting demand (Athienitis and Tzempelikos, 2002; Tzempelikos and Athienitis, 2007), reduced overall energy demand (Lollini et al., 2010), and improved daylight utilisation (Koo et al., 2010). All this provides insight into how a certain degree of responsiveness in the façade can have a beneficial effect.

This article demonstrates that the selection of a façade design can only be justified by benchmarking various design alternatives early in the design process when decisions about the façade are made (Löhnert et al., 2003). When making this comparison, it is important to simulate the performance of the façades as a result of the interaction with the building sub-systems (Lee et al., 2004; Franzetti et al., 2004). The potential energy reductions and increases in occupant comfort from the ability of dynamic façades to adapt to the considerable seasonal changes can only be achieved through an integrated process (Lee et al., 1998). For example, improving the interior daylight conditions can reduce the energy consumption for artificial lighting, but also increase the heat gain, and therefore affect the energy demand for heating, ventilation and/or cooling (Johnson et al., 1984; Tzempelikos and Athienitis, 2007; Tzempelikos et al., 2007).

The main objective of this article is to demonstrate the potential of dynamic solar shading with regard to both energy demand and the quality of the indoor environment through a series of integrated simulations. Our aim is to clarify how a number of interdependent parameters define and affect the performance of the façade. The focus is on investigating the performance of dynamic solar shading compared to fixed solar shading or no solar shading. We use integrated simulations to illustrate the importance of providing data that facilitates early design decisions with regard to the façade (Wilde and Voorden, 2004; Strachan, 2008; Petersen and Svendsen, 2010).

2. Striking a balance

Obtaining the desired equilibrium between energy demand and occupant comfort can only be achieved at room level. Only on this scale is it possible to evaluate both behaviour and requirements with regard to the thermal and the visual indoor environment defined by the occupant. The balance that results in the desired level of comfort is often highly sensitive and is represented by many environmental factors (Fig. 1).

Even minor alterations in either internal or external loads can have a relatively large impact on the energy demand for heating, cooling, ventilation or artificial lighting. Each of the façade components has a filtering effect on the external impacts, and the indoor environment can only be evaluated by considering the building envelope as a whole (Clarke et al., 1998). So the façade can be

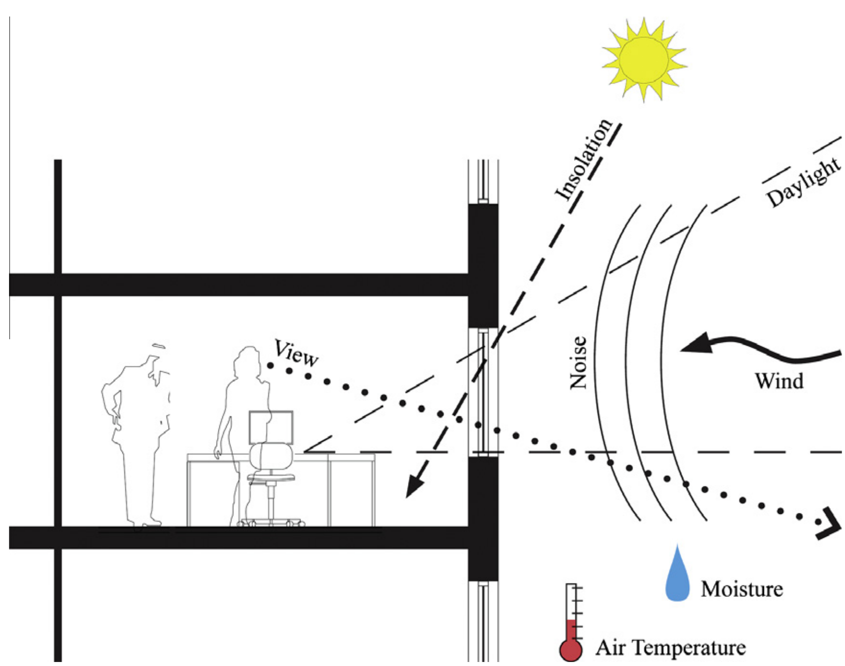

Fig. 1. Typical room with environmental components.

constructed with a number of static and dynamic components that, in combination, are capable of obtaining a better control of the outdoor climate compared with more traditional façades (Lee et al., 2002). For example: regulating the amount of solar heat gain and daylight can be obtained by installing dynamic solar shading; natural ventilation can be obtained through windows or openings (Fig. 2).

Evaluating façades with dynamic properties requires us to perform equally dynamic simulations to determine the level of indoor environment and the energy demand for heating, cooling and artificial lighting. The simulations have to include weather data for the given location and generate results for both the thermal, visual and atmospheric indoor environment – especially when considering translucent components (Selkowitz, 1998). Only then can the components be controlled in accordance with both outdoor and indoor climate, and the potential reduction in energy demand as a consequence of the increased adjustability and the utilisation of the higher luminous efficiency of daylight can be determined (Strachan, 2008). So there is considerable interdependence between the composition of the façades, daylight availability, the need for heating, cooling and artificial lighting, the layout of workplaces, and the wishes of each individual occupant.

We chose the fenestration system as a good representative for the often contradictory wishes for façades. Solar shading represents the first opportunity to control daylight and solar heat gain, which is often a key issue in obtaining workstations with sufficient amounts of daylight and avoiding overheating problems. This analysis focuses on early design decisions and therefore concentrates on the performance of dynamic solar shading in comparison with fixed solar shading and no solar shading.

3. Method

3.1. Simulation process

Analyses were carried out using iDbuild (Petersen and Svendsen, 2010), a tool developed at the Technical University of Denmark, that performs hourly-based calculations of the total energy demand taking into account the energy needed for heating, ventilation, cooling, domestic hot water and artificial lighting. In principle, the program is made up of two parts: a thermal simulation handled by BuildingCalc (Nielsen, 2005), and a daylight simulation handled by LightCalc (Hviid et al., 2008). The integrated simulation is performed by feeding hourly daylight levels into the thermal simulation program.

LightCalc essentially pre-calculates the daylight levels at given evaluation points without shading to provide initial values for the artificial lighting loads, the internal heat gain and subsequently the indoor air temperature.

3.1.1. Thermal simulation

For each hourly time step, the thermal simulation evaluates the indoor air temperature based on the solar heat gain received through the windows, and the heat exchange with internal surfaces and with the external environment. Based on the indoor air temperature, the defined heating or cooling systems are controlled to achieve given set-point temperatures. If the indoor air temperature is below the heating set point, the heating system will be activated and

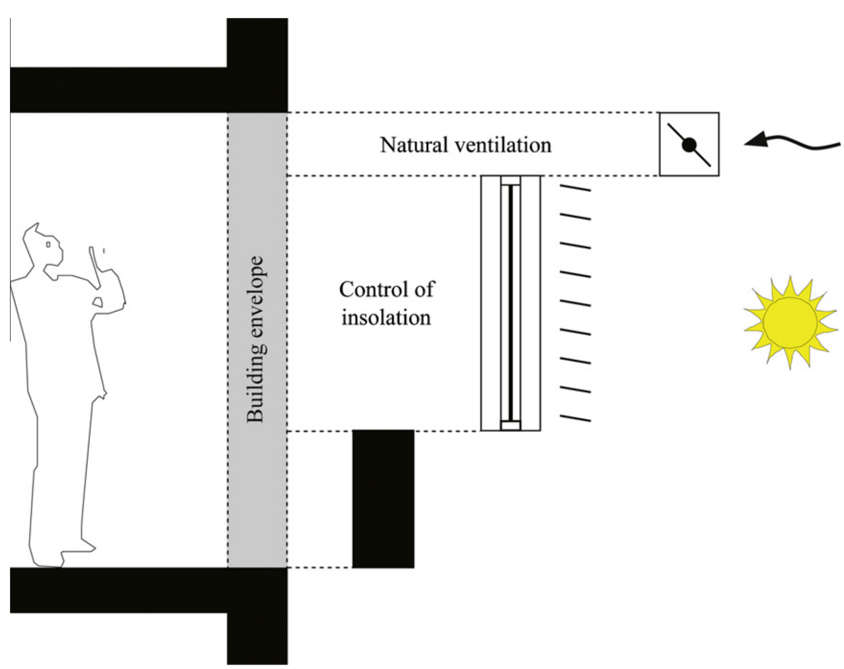

Fig. 2. Illustration of the components of the building envelope and the parameters of the external environment they can dynamically filter. Natural ventilation can be enabled through an opening above the window and controlled by a louver, while insolation can be controlled by solar shading.

if the indoor air temperature is above the cooling set point, the defined systems will be activated in the following order:

1. Shading
2. Venting (natural ventilation through windows)
3. Increased mechanical ventilation
4. Mechanical cooling

When one of these systems is activated, the thermal indoor environment is re-simulated for the given time step to include its effect and to determine the resulting indoor air temperature.

The shading system can be controlled in accordance with the indoor air temperature, the risk of glare, or both. If either of the two conditions is exceeded, the solar shading will be fully lowered and, in the case of adjustable blinds, adjusted to a cut-off angle at which direct sun is just blocked. The risk of glare is evaluated in accordance with a daylight glare probability index proposed by Wienold and Christoffersen, 2006. If controlled according to both indoor air temperature and the risk of glare, the shading system will activate if either of the two conditions occur. If shading has been activated, the angle-dependent light transmittance determined by the WIS program (WinDat, 2006) is used to calculate the daylight level at the user-defined points (see Section 3.1.2 below). The artificial lighting levels required to achieve the given set points and the resulting heat gains from the lighting are determined. Finally, the solar heat gain is calculated by using an angle-dependent total solar energy transmittance for the fenestration system (including shading system) determined by the WIS program. The solar heat gain coefficient for the fenestration system is used for both the direct and the diffuse radiation.

Venting is natural ventilation through the windows and can be activated and increased up to a given maximum air flow. Mechanical ventilation can be varied between a maximum and a minimum air flow.

Mechanical cooling is the final measure and will be activated if the indoor air temperature exceeds the cooling temperature set point after shading has been activated and both venting and mechanical ventilation has been increased to the maximum given value. Both the heating and cooling demands are determined analytically in each time step with respect to the given set-point temperatures when all other active systems controlling the indoor temperature have been activated.

3.1.2. Daylight simulation

The LightCalc algorithm calculates hourly daylight levels, controls the shading system, and determines its effect on daylight levels, making photo-responsive lighting control possible. The simulation of daylight levels as a result of both diffuse and direct components combines several approaches in determining the external and the internal light distribution.

Externally, the diffuse light from scattering in the atmosphere and from the ground and surroundings is modelled using an upper and a lower (inverted) sky dome, as suggested by Robinson and Stone (2006). The upper sky dome uses the Perez all-weather model (Perez et al., 1993) to determine the anisotropic sky radiation, while the lower sky dome is uniform with a constant luminosity expressed by a mean ground reflectance. Both sky domes are divided into 145 patches using the discretisation scheme proposed by Tregenza (1987). The internal light distribution is based on the luminous-exitance method that, like the radiosity method, treats the subdivided internal surfaces receiving transmitted direct and diffuse light as acting like light sources. The algorithms and the methodology behind the implementation are described by Park and Athienitis (2003).

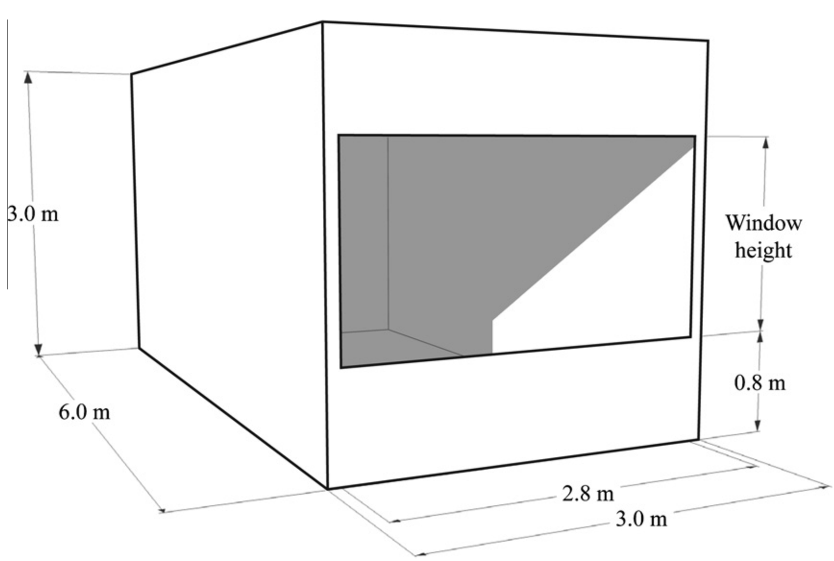

Fig. 3. Geometry of the two-person office with the window centred in relation to the room width and an offset of 0.1 m on each side. The window height was defined from a window parapet with a fixed height of 0.8 m.

The coupling between the internal and external environment is divided into three components: diffuse-to-diffuse, direct-to-diffuse and direct-to-direct. Each light component has a respective angle-dependent light transmittance calculated through WIS. When direct light hits the solar shading and diffuses, the diffuse-to-direct component is used. Interreflection between blinds and between the solar shading system and glazing is ignored.

3.2. Simulation model

The potential of the dynamic façades was investigated through a number of cases to achieve a valid and plausible estimate. Each simulation represented a $3 \times 3 \times 6$ m (width × height × depth) office space for two people, with a specific façade type and system configuration (HVAC and artificial lighting system). The window width was kept constant at 2.8 m while the window height was varied. Fig. 3 represents the model without solar shading and a window height of 1.5 m.

The room was simulated as a single unit in a larger office building located in Denmark, and only the façade was exposed to the outside climate. Ceiling, floor and internal walls were assumed to face the same thermal environment as the room investigated and their thermal capacity was included. The model was simulated in an environment without any obstructing elements.

Additional heat loss through the roof, gable and floor was added so that the energy demand of the office could still be considered representative for all rooms with the same orientation.

With respect to building services (systems) and their control, a distinction was made between 'occupancy' (8 am to 5 pm) and 'non-occupancy' (midnight to 8 am and 5 pm to midnight), and also seasonal between a 'summer' situation (weeks 1–18 and 38–53) and a 'winter' situation (weeks 19–37). The distinction between summer and winter was made in accordance with the typical heating season in Denmark (EBST, 2006) and coupled with the seasonal temperature set points defined in the European standard (CEN, 2007). The office was occupied by two people and their equipment Monday–Friday throughout the year. Table 1 contains input data on geometry, construction, system configuration, and internal loads for the simulation models.

Heating, ventilation, cooling and artificial lighting were only active during occupancy, while infiltration was constant the entire year. Natural ventilation through open windows, indicated as venting, was defined as the maximum air flow rates possible for single-sided natural ventilation during the summer season derived from the Danish standard (EBST, 2006). Set points for heating/cooling and air flow rates for mechanical ventilation corresponded with requirements for Class II in the European standard (CEN, 2007), and the power of the heating and cooling systems was assumed infinite. Both heating and cooling systems were simulated as active during occupancy the entire year, so that the system set-up would result in temperatures and air quality that always corresponded to Class II requirements.

Table 1
Input values defining the simulation model with respect to geometry, system set-up and efficiency.

Geometry	
Room – width × height × depth	$3 \times 3 \times 6$ m
Window width and height	2.8×1.5 m
Width of window frame construction	0.1 m
Constructions	
Heat transfer coefficient of opaque façade construction (*U*-value)	0.15 W/m^2 K
Heat transfer coefficient of glazing (*U*-value)	0.7 W/m^2 K
Light transmittance of glazing (LT)	0.53
Total solar energy transmittance of glazing	0.40
Heat transfer coefficient of frame construction (*U*-value)	1.5 W/m^2 K
Linear heat transmittance of window frame (Psi-value)	0.1 W/m K

Systems and internal loads	Occupancy (8 am to 5 pm)	Non-occupancy
Set-point temperatures – heating/cooling		
Summer	20/24 °C	–
Winter	23/26 °C	–
Infiltration	0.1 h^{-1}	0.1 h^{-1}
Mechanical ventilation[a]	1.48 l/sm^2	0.0 l/sm^2
Heat exchanger efficiency of mechanical ventilation[b]	0.8	–
Specific fan power, SFP	1.5 kJ/m^3	–
Venting rate (maximum)[c]	1.8 l/sm^2	0.6 l/sm^2
Mechanical cooling, efficiency (COP)	2.5	–
Internal loads from persons and equipment	10 W/m^2	1 W/m^2
General lighting		
Illuminance set point	200 lux	–
max. power	6 W/m^2	0 W/m^2
min. power (stand-by)	0.5 W/m^2	0 W/m^2
Task lighting		
Illuminance set point	500 lux	–
max. power	1.2 W/m^2	0 W/m^2
min. power	0 W/m^2	0 W/m^2

[a] Equivalent to indoor air quality Class II in the European standard EN 15251:2007 (CEN, 2007).
[b] Bypass of heat exchanger possible.
[c] Defined as ventilation through open windows. Only active outside the heating season and corresponds to maximum values for single-sided natural ventilation in Danish energy calculations (EBST, 2006).

The artificial lighting, in terms of both general and task, was controlled in accordance with daylight availability. It was assumed that work stations would be placed as close to the façade as possible. To represent a relatively conservative indication of the available daylight the evaluation point for the daylight level was placed four metres from the façade, 0.85 m above the floor and centred in relation to the room width. The assumption was made for this particular simulation model with two occupants so as to explore the full effect of photo-responsive lighting control in combination with dynamic solar shading. It would need to be re-evaluated if more occupants were added, if the layout of work stations were different, or if the overall room geometry changed. General lighting was controlled by a continuous, linear dimming profile that supplements the amount of daylight available with artificial lighting. The dimming control of the general lighting interpolated linearly between the maximum and minimum power in order to meet the specified set point (200 lux). Task lighting was either on at maximum power, if the daylight level was below the set point (500 lux), or off, if it was above the set point. It should be noted that power for both general and task lighting in Table 1 indicates a power density (W/m^2) applicable for the entire floor area. Thus, the value for the task lighting of 1.2 W/m^2 corresponds to one 11 W low-energy light bulb per occupant supplying 500 lux at the work station, whereas the general lighting at maximum power of 6 W/m^2 supplies 200 lux.

3.3. Parameter variations

A series of parameter variations were carried out in order to clarify how various solar shading types affected the indoor environment and the energy consumption. The objective was a continuous comparison of the façade alternatives to obtain a reasonable picture of the performance of the dynamic solar shading, i.e. its ability to control solar gains and thus its applicability in various situations. Three different solar shading types (no solar shading, with dynamic solar shading, and with fixed solar shading) were investigated through all these parameter variations (Fig. 4).

The fixed and the dynamic solar shading were modelled as a horizontal, grey Venetian blind with slat thickness, width and distance equal to 0.22 mm, 50 mm and 42.5 mm respectively and a reflectance of 0.54. The fixed solar shading was modelled as being fixed in the horizontal position and not retractable, and thus active during both occupancy and non-occupancy. The dynamic solar shading was modelled as pivoting and fully retractable, and during occupancy controlled according to the indoor air temperature and risk of glare. If either of the two conditions occurred, the blinds were fully lowered and adjusted to the slat angle at which direct sun was just blocked (the cut-off angle), thus maximising the amount of daylight entering the room while optimising the indoor environment with respect to glare and overheating (Hviid et al., 2008). Outside occupancy, the dynamic solar shading was only controlled in accordance with indoor air temperature.

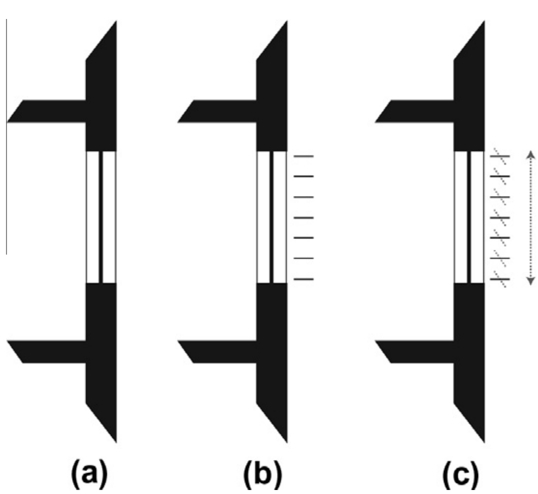

Fig. 4. Illustrations of the three different solar shading types: (a) Reference model without solar shading, (b) Model with fixed solar shading, and (c) Model with dynamic and fully retractable solar shading.

3.3.1. Design variables

Integrated daylight and thermal simulations of the three solar shading types were performed for two design variables through a number of parameter variations as seen in Table 2.

The window height in relation to façade transparency was defined from the work plane (0.8 m above the floor) and vertical upward. The width of the window was kept constant at 2.8 m, so by increasing the window height the area of the opaque façade was reduced and both the total heat transfer coefficient (U-value) of the façade and the amount of solar radiation entering the room increased. All models were simulated with the glazing and frame properties indicated in Table 1.

3.4. Evaluation criteria

Based on the simulation results, each design variable and its effect in relation to energy performance and indoor environment were evaluated. The evaluations were performed on the basis of the following parameters:

- Total energy demand of the model.
- Energy demand for heating.
- Energy demand for cooling.
- Energy demand for artificial lighting.

Table 2
For all three solar shading types, integrated simulations were performed for each of the four major orientations and three different window heights.

What	Why	How	Simulated models
Orientation	Influences the incident amount of solar radiation the façade receives	Orientation of window	North, south, east and west
Façade transparency	Defines the amount of heat gain and daylight that enters the room	Window height	1.0 m, 1.5 m and 2.0 m

Table 3
List of primary energy factors as stated in the Danish building regulations (EBST, 2006) and how they are used in the simulations.

Energy source	Factor	Simulation model
Gas, oil and district heating	1	Space heating and domestic hot water
Electricity	2.5	Cooling, fans for mechanical ventilation and artificial lighting

- Daylight represented by the daylight factor and usable area for workstations.

To assess the total energy demand as required in the energy directive from the European parliament (EPBD, 2002), a domestic hot-water consumption of 100 l/m^2 corresponding to the Danish standard for offices was added. Energy performance was evaluated using primary energy factors as indicated in Table 3 corresponding to the Danish building regulations (EBST, 2006).

The thermal indoor environment and the air quality were both evaluated in accordance with the European standard EN 15251:2007 (CEN, 2007). The heating and cooling set points and the air flow for the mechanical ventilation corresponded to the requirements for indoor environment Class II. The energy demand for ventilation was equal for all models since the specific fan power and the airflow was constant, also corresponding to indoor environment Class II. Because the available heating and cooling power was assumed to be infinite, the requirements for indoor environment Class II with respect to thermal environment and air quality were always fulfilled for all models during occupancy. It should be noted, however, that while the heating and cooling systems were both simulated as active all year during occupancy and therefore resulted in an increased consumption, they do render possible a simple and clear comparison of the performance of the different façades. Since the requirements for the quality of the indoor environment were fulfilled, the energy used for heating, cooling and artificial lighting gives a clear indication of the façade's ability to control both internal and external impacts to maintain a good indoor environment.

The addition of natural ventilation (venting) outside the heating season was made to clarify whether or not some façade designs for certain orientations performed well enough to render cooling obsolete. E.g. problems with overheating outside the heating season would either not exist or be small enough to be handled by an increased air flow obtained through natural ventilation.

The amount of daylight available was evaluated based upon the daylight factor in the working plane (0.85 m above the floor) and simulated using the CIE standard overcast sky, which delivers 10,000 lux on an outside unobstructed horizontal surface. The daylight factor indicates the ratio between the daylight on an internal surface and the daylight on an unobstructed external surface and will therefore not differ in accordance with orientation, day or hour. Whether or not workstations could be established was defined by a daylight factor threshold of 2%, which under a CIE standard overcast sky corresponds to an illuminance level of 200 lux. The threshold connects to the general lighting level and thus corresponds to the illuminance set point for the general lighting as defined in Table 1.

4. Results

Comparative data with respect to both energy demand and daylight factors are presented below for the three solar shading types: no solar shading, fixed solar shading, and dynamic solar shading.

4.1. Energy demand

The data are arranged according to window height and orientation. All models were simulated for an entire year and the results correspond to the annual energy demand per square metre (kWh/m^2 per year). As seen in Fig. 5, all the simulated models resulted in an energy demand below 70 kWh/m^2 per year, and approximately 22% of the models (7 out of 36) show an energy demand below 50 kWh/m^2 per year. The best-performing façade faced south, with a window height of 1.5 m and dynamic solar shading, whereas the worst-performing façade faced north, with a window height of 1.0 m and fixed solar shading. The two façades, best and worst, were simulated to have a total energy demand of 46 kWh/m^2 per year and 66 kWh/m^2 per year, respectively.

Generally, the façade with dynamic solar shading had the best performance with respect to total energy demand. In most cases, façades with fixed solar shading had the worst performance, except for façades facing south, east and west with a window height of 2.0 m, where the façades with no solar shading had the worst performance. The vari-

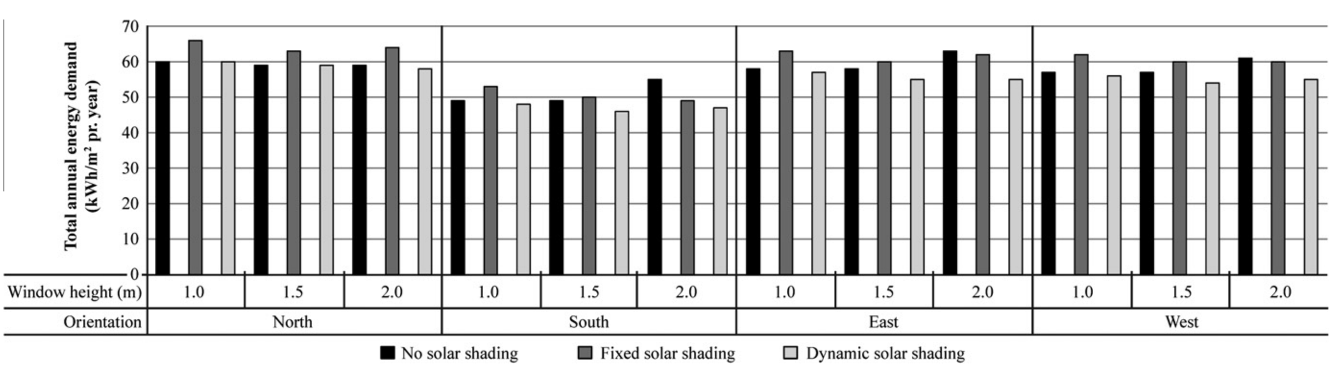

Fig. 5. Annual energy demand for simulated models depending on orientation, window height and solar shading types.

ations in energy demand between the three different solar shading types were generally of the same magnitude in all cases. Because air flow rates were determined in accordance with indoor air quality (number of occupants and floor area) as defined in the European standard (CEN, 2007), energy demands for ventilation and for domestic hot water were constant for all models corresponding to 13 kWh/m^2 per year and 5 kWh/m^2 per year, respectively. Subsequently the differences in total annual energy demand were caused by differences in the energy demand for heating, cooling and artificial lighting.

The distribution of energy demand for heating, cooling and artificial lighting, as seen in Figs. 6–9, shows that the north, east and west-facing façades have an increased heating demand when the window height (i.e. the façade transparency/window area) is increased due to the greater heat transmission through the glazed component than through the opaque parts. South-facing façades have a varying tendency depending on the solar shading types. For all models, the energy demand for artificial lighting decreases as the façade transparency and the insolation increases. The energy demand for cooling generally increases as the window height increases, but the increase is proportionally greater in the cases without solar shading for the orientations south, east and west (Figs. 6–9).

4.2. North

Models with façades facing north showed a reduction in total annual energy demand between the worst (at 66 kWh/m^2 per year) and the best-performing façade (at 58 kWh/m^2 per year) amounting to approximately 12% (Fig. 6). The north-facing façades with no solar shading or fixed solar shading had the best performance at a window height of 1.5 m, whereas the façades with dynamic solar shading had the best performance at a window height of 2.0 m. All the performance indicators showed similar tendencies and magnitudes for all types of solar shading. When the window height was increased, the heating and cooling demand increased and the energy demand for artificial lighting decreased.

4.3. South

Models with façades facing south showed a reduction in total annual energy demand between the worst (55 kWh/m^2 per year) and best-performing façade (46 kWh/m^2 per year) amounting to approximately 16% (Fig. 7). The façade with no solar shading performed equally well with window heights of 1.0 m and 1.5 m. The façade with fixed solar shading had the best performance at a window height of

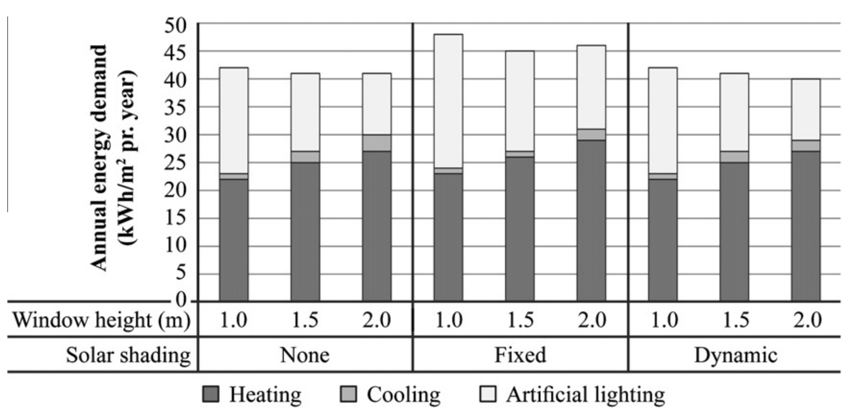

Fig. 6. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing north.

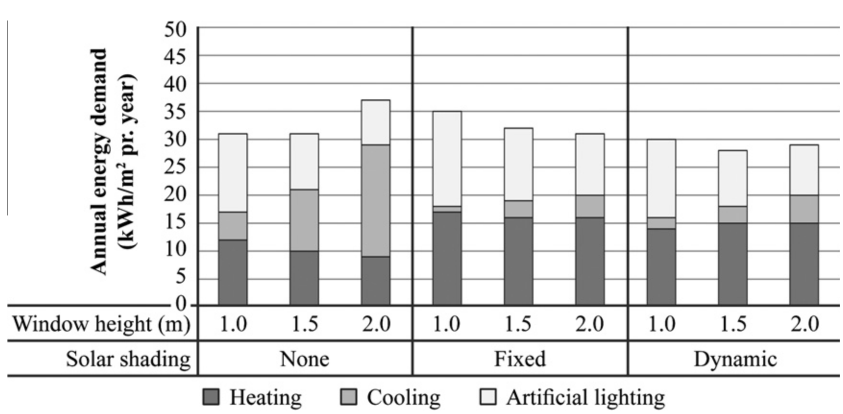

Fig. 7. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing south.

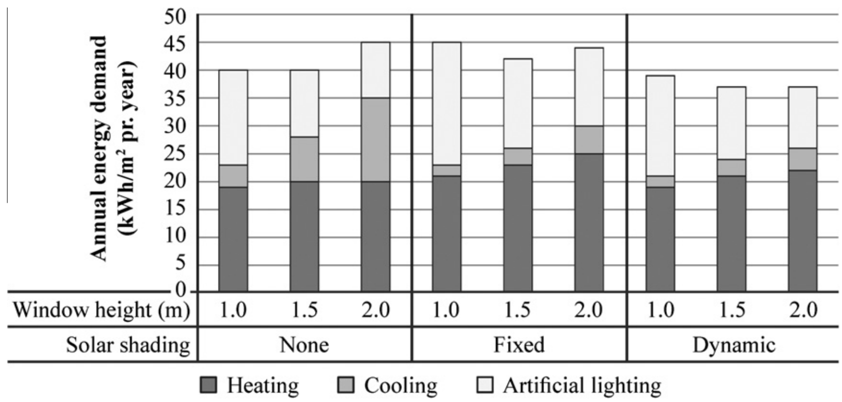

Fig. 8. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing east.

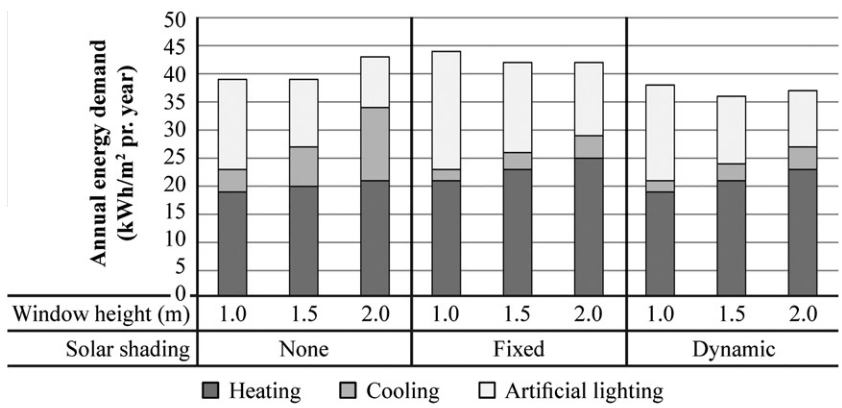

Fig. 9. Distribution of annual energy demand for heating, cooling and artificial lighting for simulation models with façades facing west.

2.0 m, whereas the façade with dynamic solar shading had the best performance at a window height of 1.5 m. The tendencies of the performance indicators were similar for façades with fixed and with no solar shading, but the magnitudes differed. When the window height was increased, the heating and lighting demand decreased while the cooling demand increased. Façades with dynamic solar shading displayed an increase in heating and cooling demand, but a decrease in energy demand for artificial lighting. The façades with no solar shading displayed considerable interdependence between all the performance indicators: increasing the window height resulted in an increased cooling demand that exceeded the combined decrease in energy demand for heating and artificial lighting. The façades with fixed or dynamic solar shading showed similar magnitudes of variation between the performance indicators.

4.4. East and west

Models with façades facing east showed a reduction in total annual energy demand between the worst (63 kWh/m^2 per year) and best-performing façade (55 kWh/m^2 per year) amounting to approximately 13% (Fig. 8). The east-facing façade with no shading performed equally well at window heights of 1.0 m and 1.5 m. The east-facing façade with fixed solar shading had the best performance at a window height of 1.5 m, whereas the façade with dynamic solar shading performed equally well at window heights of 1.5 m and 2.0 m.

Models with façades facing west showed a reduction in total annual energy demand between the worst (62 kWh/m^2 per year) and best-performing façade (54 kWh/m^2 per year) amounting to approximately 13% (Fig. 9). The west-facing façade with no shading performed equally well at window heights of 1.0 m and 1.5 m. The west-facing façade with fixed solar shading performed equally well at window heights of 1.5 m and 2.0 m. The west-facing façade with dynamic solar shading had the best performance at a window height of 1.5 m.

For east and west-facing façades, all the performance indicators showed similar tendencies for all window heights and types of solar shading. When the window height was increased, the energy demand for heating and cooling increased and the energy demand for artificial lighting decreased. All east and west-facing façades showed a proportionally greater difference in the energy demand for artificial lighting when the window height increased from 1.0 m to 1.5 m compared to an increase in window height from 1.5 m to 2.0 m. For east and west-facing façades with no solar shading, the energy demand for cooling was greater than for façades with fixed or dynamic solar shading.

4.5. Daylight

The amount of daylight for the three different types of solar shading at window heights of 1.0 m, 1.5 m and 2.0 m are presented in the form of daylight factors and depicted in Fig. 10, with the threshold of a 2% daylight factor indicated. Because of the uniform overcast-sky conditions, the dynamic solar shading was not activated and daylight factors for models with no solar shading and models with dynamic solar shading were equal.

In general, the daylight factor decreases as the distance from the façade increases and the window height decreases. The results group the performances of the façades with respect to daylight factors via varying dependence on the distance from the window. The façades with no solar shading or with dynamic solar shading displayed a greater dependence on the distance from the window compared to the façades with fixed solar shading, and they displayed a more dramatic decrease in the daylight factor as the distance from the façade increased than did façades with fixed solar shading. The difference between the two groups was greatest close to the façade and decreased as the distance from the façade increased, so that daylight factors tended to converge at the back of the room, but still with considerable differences. However, where the window height was the same, façades with no solar shading and façades with dynamic solar shading always performed better with respect to daylight than façades with fixed solar shading.

With regard to the amount of daylight, only façades with a window height of 2 m with no solar shading or with dynamic solar shading provided a daylight factor of a minimum of 2% in the entire working zone. Under CIE overcast-sky conditions, only these façades provided an illuminance of minimum 200 lux for the area extending 4 metres from the façade and thereby enough daylight for the general lighting to be dimmed to the minimum effect indicated in Table 1. Reducing the window height to 1.0 m or 1.5 m reduced the distance from the façade where a minimum of 2% daylight factor could be maintained to 2.25 or 3.5 m, respectively. For façades with fixed solar shading, window heights of 1.0 m, 1.5 m and 2.0 m meant that the distance from the façade where a minimum of 2% daylight factor could be maintained was approximately 1.0 m, 2.0 m and 3.0 m, respectively.

5. Discussion

The results for the simulated parameter variations illustrate that even in the relatively cold north-European climate, where heating often dominates the total energy consumption, energy demand for cooling and artificial lighting are also important – especially in low-energy buildings. General for all orientations, of course, is that increased façade transparencies allow more insolation into the room. A general tendency that is observed is a reverse proportionality between cooling and artificial lighting. However, the energy demand for heating and cooling depends not only on increased insolation, which varies greatly depending on the orientation, but also on the change in the thermal performance of the façade that occurs when glazing replaces an opaque façade. Furthermore, our simulations of the daylight factors showed a much greater difference in performance between façades with no solar shading or with dynamic solar shading and façades with fixed solar shading.

The results for the cases examined show that in most cases dynamic solar shading constitutes the best design alternative, but also that the difference in total energy demand between the best and the second best are minor and can be non-existent. Thus, when all results are considered, the difference in total energy demand between the worst and the best-performing façade for a given orientation does not exceed 16%. With respect to energy, façades

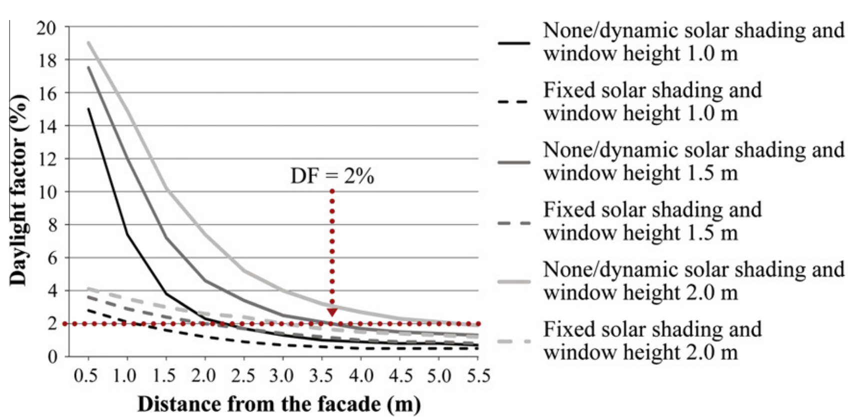

Fig. 10. Daylight factors in the working plane (0.85 m above the floor) along the centreline in the room in relation to the distance from the window depicted by solar shading type and window height, using the CIE overcast sky. Daylight factors for façades with no solar shading and façades with dynamic solar shading are equal because the dynamic solar shading would not be activated under overcast-sky conditions. The threshold of a 2% daylight factor corresponding to 200 lux when the illuminance on an outside unobstructed surface is 10,000 lux has been indicated.

with fixed or no solar shading are a relevant alternative for all façades facing north and for façades with window heights of 1.0 m or 1.5 m facing south, east and west. But when it comes to daylight factors, dynamic solar shading shows a dramatic improvement in performance over fixed solar shading. The increased daylight factor results in an expansion of the well-lit area by 70–150%. The increased amount of daylight available provided by a dynamic solar shading more adaptable to the climate, therefore allows a greater and more flexible utilisation of the space, so that more work stations can be established. The façade design, the geometry of the room and its function should therefore be considered simultaneously. It should be noted that the daylight factor, although a simple indication of a worst-case scenario, is still a measure used to document the amount of daylight. Furthermore, the energy demand for the photo-responsive artificial lighting with a continuous dimming profile controlled in accordance with weather data will ultimately reflect the amount of daylight available similar to the daylight autonomy. Thereby the two measures together satisfactorily indicate the façade's performance with respect to daylight. Thus the results prove the importance of integrated simulations to quantify the potential of dynamic fenestration systems due to the great interdependence of the various parameters. Furthermore, this quantification needs to be performed in the early stages of the design process, where essential design decisions defining the framework and preconditions for the building's performance are made – not only to obtain a more complete performance assessment, but also to better tailor the façade design to the actual building, its layout and its function. Open plan offices with work stations far from the façade require high façade transparency and a dynamic solar shading to obtain sufficient amounts of daylight without having problems with overheating, whereas fixed solar shading could be considered for a one or two-person office where work stations can be established close to the façade.

Dynamic solar shading with its ability to reduce energy consumption and improve occupant comfort may therefore not always be the optimal choice when economics (acquisition and maintenance) or subjective factors such as aesthetics are included.

Each simulation was only performed on a single, but representative room in the perimeter zone of a building, and the interaction with the rest of the building was considered as increased transmission heat loss through the roof, gable and floor. The actual performance of the entire building depends not only on the control strategy chosen for each room, but on the control strategy for the entire building. However, our focus was on depicting the performances of different façade designs and the importance of considering alternatives. iDbuild provides adequate information for the comparison and evaluation of various alternatives in respect to both indoor climate and energy consumption.

It should be noted that the results represent a building placed in a totally unobstructed environment and therefore with a high degree of daylight available. In an urban environment, where a smaller amount of daylight is available, the potential disadvantage of permanently reducing the amount of daylight by implementing fixed solar shading and thereby increasing the energy demand for artificial lighting is not fully disclosed. Moreover, this article focuses on comparing façades with no solar shading with one specific type of dynamic and fixed solar shading. Therefore the results cannot be used for an evaluation of dynamic solar shading or dynamic fenestration systems in general. However, investigation of other dynamic façade components will form part of our future work. Furthermore, the highly glazed façades which seem to be a prevailing element in modern office buildings mean that dynamic solar shading is very relevant for the control of large amounts of insolation and minimise the risk of overheating, while still providing views of the outside. This relevance will only increase when the stricter demands for "nearly zero-energy buildings" are implemented in 2020 (EPBD, 2010).

6. Conclusion

To quantify the potential of dynamic solar shading, we have presented simulation-based results from an investigation of three different solar shading types. Integrated thermal and daylight simulations were carried out to demonstrate comparable results of the performances of the façades with respect to energy consumption and indoor environment. The performances of the façades were evaluated in terms of total energy demand, the individual energy demands for heating, cooling and artificial lighting, and also the amount of daylight in terms of daylight factor. The quality of the indoor environment for all the models simulated complied with Class II defined in the European standard CEN 15251, 2007.

For a typical office located in Denmark, the significance of orientation, window area and solar shading types was investigated to emphasise the importance of involving design alternatives in the early stages of design, when critical decisions on the design of the façade are made. The work presented demonstrates how an available open source program can perform integrated simulations, reveal a high degree of interdependence between parameters, and thus make it possible to quantify a façade's performance in a given context and achieve harmony between the layout of the building and its functions.

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