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Control Strategies of an Adaptive Glazing

Dr. Volker Ritter[1], Christoph Matschi[1], Dr. Daniel Gstöhl[1] and Prof. Dietrich Schwarz[1]

[1] University of Liechtenstein, Institute for Architecture and Planning, Chair of Sustainable Design, Vaduz, Liechtenstein

Abstract

Controlling the solar transmittance of glazed office buildings that are facing the sun is not only crucial to ensure high thermal comfort but also to minimize the cooling and heating demand of the building. Often the solar and visual transmittance of glazing installed in high office buildings is constant, as adjustable external shading elements are not possible to install, because of maintenance issues. Within the research project titled Fluidglass, a new glazing will be developed that has fluid chambers, which can be circulated and colored, to control the solar and visual transmittance and to collect heat in the fluid. This paper presents an assessment of the different control strategies that set the concentration of the colorant in the fluid chamber of the glazing.

The assessment shows that certain control strategies have high potential for reducing the energy demand for heating and cooling depending on the locations (Munich 20-30%, Madrid 50-70%, Dubai 50-60%). However, they can also causes an increase of the electricity demand for lighting, which needs to be considered in the further development. In general, control strategies that only consider the solar irradiation are less promising than controls that also take the interior temperature into account. The results for controls that also respect the thermal comfort based on a Predicted Mean Vote index (PMV) can achieve low energy demand, presuming that a deviation from the highest level of comfort is acceptable. At this stage of research, none of the studied control strategies shows to be optimal for all climate conditions to achieve highest energy reductions. Further research is necessary in the development of a control strategy that can universally be applied.

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1. Background

Glass is widely used as construction material of building facades not only in temperate, but also in hot climate. This is due to aesthetical benefits that an unobstructed view provides. However, large areas of glazing not only affect the heating demand in cold regions (caused by the thermal heat transfer from the interior to the exterior), but also the cooling demand in hot regions, because of uncontrolled high solar heat gains. The latter is especially challenging in operation of high-rise office buildings with considerable high internal heat gains and no possibility for natural cross ventilation with operable windows. Often glass with high reflectivity and low transmittance is installed, which not only reduces the solar transmittance, but also the visual transmittance permanently. As a result, electrical lighting is required to operate at days with low solar irradiation to ensure enough luminance at the working desks in distance to the façade.

The driving idea of this research project is developing an adaptive glazed façade element that allows controlling the solar transmittance within the glazing element to benefit from higher solar heat gains when needed during the heating season and to reduce solar heat gain during the cooling season while ensuring enough day light. Up to now, the issue of adjustable transparency is achieved by using electro-chromic materials, liquid crystals and electrophoretic or suspended-particle devices (Baetens, 2010). In this research project, solar transmittance will be controlled by a fluid layer in between two panes of glass facing the exterior, which can be circulated and changed in its transparency. Another fluid layer orientated to the interior allows for heating and cooling. Figure 1 illustrates a schematic section of the currently considered assembly of the glazing unit, which has been described in detail by Gstoehl et al. (Gstoehl, 2011) and Stopper et al. (Stopper, 2013). The configuration is from here on referred to as Fluidglass. The fluid in the chamber facing the exterior (exterior fluid chamber, FCe)

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controls the transmittance during the hot season due to a colorant in the fluid, which can be changed in its concentration. This layer also acts as solar thermal collector, especially if the concentration of the colorant is high. The fluid in the chamber facing the interior (interior fluid chamber, FCi) can be operated as cooling or as heating panel by circulating water with the according temperature. During the cold season the FCe is not operated. Fluid inlet temperature and mass flow rate affect the power of each fluid chamber. This also affects the efficiency of the FCe as thermal solar collector.

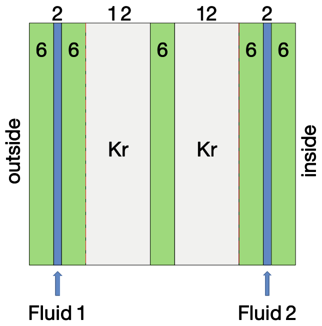

Figure 1: Section of the currently considered composition of the Fluidglass [mm], green = pane of glass, blue = fluid layer, dashed red = heat reflecting coating, grey = inert gas filling

The development of the Fluidglass is subject of a research project in collaboration with eleven project partners in Europa, which received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 608509. During the first phase of the project, the simulation of the Fluidglass should provide relevant information about the potentials, but also support decisions regarding the type of materials used in the glazing unit. This paper is a potential assessment regarding the possibility for energy reductions depending on the control strategy for operating the colorant concentration in the fluid. The project is based on and profits from previous research projects (Eiband 2004), which had partly be funded by the government of Liechtenstein. Figure 2 shows a Fluidglass prototype built in previous projects, which is in operation with a colored fluid in a fluid chamber. The image illustrates the reduction of solar and visual transmittance already at relative low concentration of the colorant.

Figure 2: Prototype developed in a previous research project in operation with circulating colored fluid in a chamber (Eiband 2004)

2. General settings of the model

The full potential of Fluidglass can only be assessed in a complex dynamic building simulation. The TRNSYS (TRNSYS, 2014) model developed for this first analysis is a simplification that considers the benefits that controlling the transmittance of the glazing provides in comparison to regular glazing. The model calculates the annual heating and cooling demand and the electricity demand for lighting at the three locations Munich, representing a cold-temperate climatic condition, Madrid, representing a hot-temperate climatic condition, and Dubai, representing an subtropical climatic condition.

The model space complies with the reference space described in the technical standard VDI 2078:2012-03 (VDI 2012), which reflects an office space of $17.5m^2$. This model space is further differentiated in terms of thermal mass with five classes, varying from extremely heavy to extremely light. Beside the fully glazed vertical façade that is orientated to the South, all remaining walls, the floor and the ceiling are designed to be adiabatic. The overall heat transfer coefficient of the glazing is 0.7 $W \cdot m^{-2}\ K^{-1}$, calculated at standard reference conditions. The area is 15% of the overall opening, which has an heat transfer coefficient of 2.3 $W \cdot m^{-2}\ K^{-1}$. The transmittance of the Fluidglass configuration with clear fluid in the fluid chambers is calculated with the software Optics6 and Window7.2. The considered colorant in the FCe and the FCi already affects the visual and solar transmittance with relatively low concentrations. The visual and solar transmittance of the colorant changes proportionally with rising concentration of the colorant. The visual transmittance always stays above the solar transmittance, which is beneficial for the visual comfort.

The internal load is set according to DIN 4108-2:2013-02 (DIN 2013) with 13 $W \cdot m^{-2}$ representing the load from user, appliances and lighting. Further settings for infiltration and ventilation are also according to this standard, with a typical air exchange rate (including infiltration) of $1h^{-1}$ if users are present and an infiltration rate of 0.24 h^{-1} if users are absence. The model also includes an operation mode with increased ventilation rate of 3 h^{-1}, which represents night cooling during the hot season. The assessment with the software EES allows a first estimation of the heating and cooling power of the FCi. Assuming an inlet temperature of 18°C and an interior air temperature of 26°C, the cooling power at a mass flow rate of 2 $kg \cdot min^{-1}$ per running meter of Fluidglass is about 50 $W \cdot m^{-2}$ pane of glass. The heating power of this pane of glass is about $70W \cdot m^{-2}$, based on an inlet temperature of 30°C and a mass flow rate of 2 $kg \cdot min^{-1}$ per running meter of Fluidglass. The cooling and heating power in the model are conservative estimations, which obviously depend on the mass flow rate and the inlet temperature, but also on the boundary conditions, which change. In particular, the concentration of the colorant in the FCe affects the temperature of the fluid during solar irradiation. A more detailed model is currently in design stage to more exactly calculate the temperature differences in the assembly.

The reference model is basically identical to the model described above, beside the type of glazing. This model is equipped with solar glazing that has a solar transmittance of 0.177 in combination with a visual transmittance of 0.436. This approximately corresponds Fluidglass with a colorant concentration of 1%. Furthermore, The overall heat transfer coefficient of the glazing with 0.7 $W \cdot m^{-2} \cdot K^{-1}$ matches the heat transfer coefficient of the Fluidglass at standard reference conditions. The electricity demand for lighting is in all considered cases based on the assumption that 4.2 fluorescence light bulbs are required to illuminate the space, which cause an power demand of 21.6 W per square meter office space.

1. Settings of the Control Strategies

The model allows comparing five control strategies of the colorant concentration. The nature of the rule based control strategies is to be reactive and not predictive. Each control strategy is active the entire year. In general, all control strategies set the concentration of the colorant to maximum if the interior air temperature, T_{int}, rises above 25°C, since first approximation regarding the cooling power of the Fluidglass indicate that this power is limited and cannot provide enough cooling for the considered office space if low transmittance allows high solar irradiation to overheat the space during the hot season.

The solar irradiation is key parameter of the first control strategy (CS1). The standard DIN 4108-2:2013-02 (DIN 2013) provides recommendations for simulating shading controls for office spaces. According to this standard, shading is required if solar radiation exceeds 200 $W \cdot m^{-2}$ global irradiation on the glazing. The purpose of this is to avoid overheating during the hot season. However, this strategy sets the colorant concentration to a maximal or minimal set point.

The second control strategy (CS2) sets the colorant concentration based on the illuminance in the interior space. According to DIN15251:2007 (DIN 2007), a minimal interior illuminance of 500 Lux is required at the center of the space on working desk level to guarantee comfortable working conditions. Simulations with the software ReLux-Pro (ReLux, 2012) show that a minimal illuminance of 1700 Lux is required directly behind the Fluidglass to allow for the required of 500 Lux at the working desk level (Böing, 2013). Depending on the colorant concentration, this level of illuminance is reached at different levels of solar irradiation. While 26 $W \cdot m^{-2}$ are enough if the fluid of the Fluidglass is uncolored, more than 258 $W \cdot m^{-2}$ are required if the concentration of the colorant is 3%. Table 1 lists the colorant concentrations that ensure the required 500Lux.

Table 1: Benchmarks of the second control strategy (CS2), controlled by the solar radiation [I_0].

	I_0 >26 $W \cdot m^{-2}$	I_0 >55 $W \cdot m^{-2}$	I_0 >214 $W \cdot m^{-2}$	I_0 >258 $W \cdot m^{-2}$
Colorant concentration	0%	1%	2%	3%
Solar transmittance T_{sol} [-]	0.34	0.17	0.05	0.04
Visual tansmittance T_{vis} [-]	0.65	0.31	0.09	0.07

The disadvantage of CS1 and CS2 is that the interior air temperature, which accounts for the heating and cooling demand, is at best indirectly considered. This is taken into account in the third strategy (CS3), where the colorant concentration is gradually changed with the rising interior air temperature [T_{int}]. This ensures that solar irradiation generates interior heat gains if the room temperature is below the benchmark of 21°C, but also reduces the solar irradiation gradually if higher temperatures are reached. The colorant concentration is set to maximum if T_{int} exceeds 25°C. This, however, also reduces the visual transmittance considerably. At days with low solar irradiation and high concentration of the colorant in the fluid of the Fluidglass, electrical lighting is required to ensure 500Lux interior illuminance at the center of the space at height of a work desk. Table 2 lists the controls of the colorant concentration and the according transmittances.

Table 2: Benchmarks of the third control strategy (CS3), controlled by the interior air temperature [Tint].

	T_{int} <=23°C	T_{int} >23°C	T_{int} >24°C	T_{int} >25°C
Colorant concentration	0%	1%	2%	3%
Solar transmittance T_{sol} [-]	0.34	0.17	0.05	0.04
Visual tansmittance T_{vis} [-]	0.65	0.31	0.09	0.07

The fourth control strategy (CS4) aims for high level of thermal comfort. This is provided by controlling the Predicted Mean Vote Index (PMV), which P.O.Fanger developed (Fanger, 1970). This index complies with ANSI/ASHRAE Standard 55 (ASHRAE 2013). The PMV is a measurement for the thermal sensation, given as

PMV-Index. The PMV-Index is scaled by a seven point psycho-physical scale which ranges from -3 to +3. Negative values indicate the thermal sensation as too cold, positive values as too warm and the zero point as neutral. The PMV-Index is calculated by the PMV-equation, which is more or less an energy balance of the human body. The control strategy CS4 allows a deviation of the PMV in the range of -0.2 to +0.2. Presuming this is provided, the concentration of the colorant is chosen based on T_{int}, as shown in Table 3. If the PMV exceeds the benchmark +0.2 or falls below -0.2, the concentration of the colorant is set to 0% to allow for maximal solar heat gains.

The fives control strategy (CS5) is basically the same as the control strategy CS4, beside this control aims of medium level of thermal control. Consequently, this control allows the PMV ranging from -0.5 to +0.5. Table 3 lists the criteria of control CS4 and CS5.

Table 3: Colorant concentrations for the fourth and fives control strategies (CS4 and CS5), combining interior air temperature [T_{int}] and solar radiation [I_0], presuming the PMV index is within the according range of -0.2 to +0.2 for CS4 and within the range of -0.5 to 0.5 for CS5.

	I_0 >26 W·m^{-2}	I_0 >55 W·m^{-2}	I_0 >214 W·m^{-2}	I_0 >258 W·m^{-2}
T_{int} > 25°C	3%	3%	3%	3%
T_{int}=22°C…25°C	0%	1%	2%	3%
T_{int} < 22°C	0%	0%	0%	0%

Besides reducing the cooling demand, the purpose of the exterior fluid chamber FCe is to operate as solar thermal collector. The efficiency of this collector depends on the concentration of the colorant. A separate model has been developed with the software EES to calculate the outlet temperature of this fluid chamber. Based on the temperature differences between fluid outlet and inlet, the efficiency of the exterior fluid chamber as collector is determined. This information is used within TRNSYS as input for the simulation of an unglazed solar thermal collector. The model calculates the heating and cooling demand based on ideal building systems with maximal efficiency. It is assumed that a hot water tank exists in the building that allows storing the daily gained heat from the Fluidglass collector, which is used for reducing the daily space heating demand. This is a simplification of real heating systems.

2. Results

In general, the different thermal mass of the five building types of the reference case result at the three considered locations in considerably different heating and cooling demand, as shown in Figure 3. The building type “XL” denotes an extremely light building, while the type “XH” denotes a building that is extremely heavy. In between is the building type “M” that denotes an average building. While rising thermal mass is beneficial in cold- and warm-temperate climate of Munich and Madrid, high thermal mass is counterproductive at locations like Dubai, where stored heat in the building mass is less often possible to be released by night cooling etc. The electricity demand for lighting is generally lower at hotter locations.

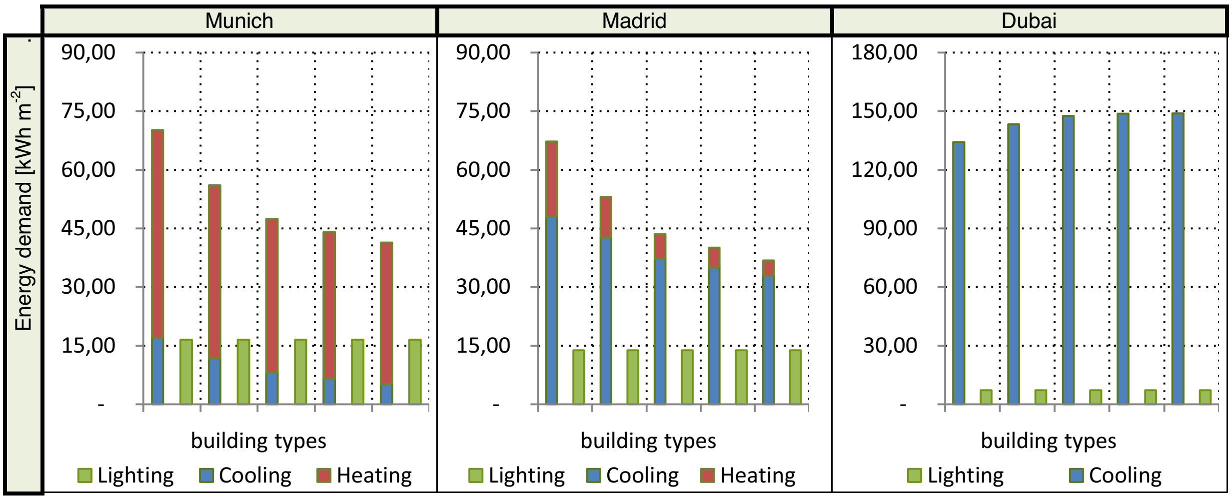

Figure 3: Resulting annual energy demand [kWh/m²] for heating, cooling and electrical lighting in Munich, Madrid and Dubai for extremely light (XL), light (L), medium (M), heavy (H) and extremely heavy (XH) buildings

Accordingly, the location and building type affects the results of the simulations with the Fluidglass model. In the following chapter, only the results of the control strategies are only shown for the building type M, because the results of the other building types basically follow the same trend. The bar diagrams in Figure 4 show heating demand, cooling demand and electricity demand for lighting the space for the reference case type M (Ref) and each control strategy (CS).

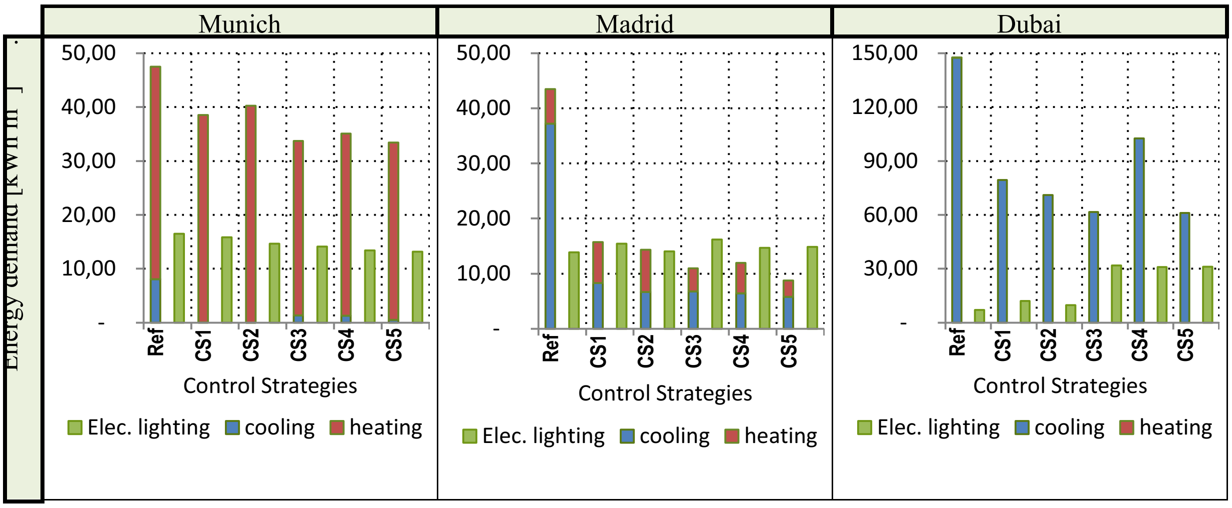

Figure 4: Resulting annual energy demand [kWh/m²] of heating, cooling and electrical lighting of the building type M, generated with the different control strategies (CS) in Munich, Madrid and Dubai

2.1. Control strategy CS1

The control strategy CS1, which is based on solar irradiation without taking interior temperatures into account, causes in Munich and Madrid not a significant reduction of the annual heating demand compared to the reference case. This is mainly because of less heat gains generated in the space, since the colorant concentration can become high also during the cold season if the solar irradiation perpendicular to the glass exceeds the limiting benchmark of 200 $W \cdot m^{-2}$. However, the cooling demand is considerably reduced in both cases. It becomes almost negligible in Munich. A considerable reduction of the cooling demand is also the result in Dubai, where this control strategy almost halves the cooling demand. This considerably affects the energy demand in Dubai, as the energy demand in the permanent hot climate is mainly driven by the cooling demand. It is necessary to note that heat gains in the fluid chamber need to be fed to a heat sink, which can be energy intense depending on the building system. The rising electricity demand for lighting in Madrid and Dubai is due to the reduced illuminance during the working hours.

2.2. Control strategy CS2

The control strategy CS2, which is based on the illumination, causes an increase of the heating demand and a reduction of the cooling demand in Munich and Madrid. The heating demand even exceeds the heating of the reference case in Munich. This is again due to lower passive solar heat gains. Apparently, the control strategy with more set points allows for more hours during the cold season when the fluid is colored, which lowers the passive heat gains. However, results of the model are based simplified heating and cooling system. Assuming the building is equipped with a heat storage that can store the heat surplus for a longer period, the results would become different, especially during spring and fall with series of days where periods with heat surplus alternate with a series of days with heating demand. Again, this control reduces the cooling demand considerably in Madrid and Dubai, even more than with the control strategy CS1. This is because of an earlier start of reducing the solar transmittance compared to the control strategy CS1. Furthermore, the control strategy CS1 only knows the settings minimal and maximal transmittance, while the strategy CS2 has two steps in between. The electricity demand for lighting becomes lower with this control strategy, since the control takes the criteria 500 lux into account.

2.3. Control strategy CS3

The results of the control strategy CS3, which controls the concentration of the colorant based on the illuminance and the interior air temperature [T_{int}], results in a lower overall energy demand in Munich and Madrid compared to the reference case. This control indirectly considers the seasonal changes and only allows for a colorant in the fluid if Tint is above 23°C. In comparison to the control strategy CS2, the control strategy CS3 generates less heat gains and is a more reasonable strategy if the building is not equipped with a heating system that can be exploited heat gain from Fluidglass. While the control strategies CS1 and CS2 result in approximately the same energy demand compared to the reference building, the control strategy CS3 allows for a reduction of roughly 25% in Munich. Furthermore, the electricity demand in Munich is lower too, since good illumination is one criteria of the control. However, the electricity demand for lighting rises in Madrid. This is because of the criteria that maximal concentration of colorant is chosen, if T_{int} is higher than 25°C, which needed to be set, since first approximations show that the cooling power of the Fluidglass is limited. While the control strategy CS3 further reduces the cooling demand in Dubai compared to the control strategy CS2, the cooling demand in Madrid remains on the same level. However the electricity demand for lighting rises considerably in Dubai with this control strategy. Apparently, this control strategy more often sets the concentration of the colorant to the maximum of 3%, which on the one hand reduces the cooling demand, but also causes the electricity demand to rise, since the illuminance at the relevant position is below 500 lux.

2.4. Control strategy CS4

This control strategy, which provides a very high level of thermal comfort, increases the annual heating demand in Munich a little compared to the control strategy CS3. This is because of the five additional criteria that influence thermal comfort, beside the room air temperature. These criteria are metabolic rate, clothing insulation, mean radiant temperature, air speed and relative humidity. It is necessary to further study, which of the five criteria is the main driver of this result. Currently, it is assumed that the clothing insulation that is on high level and the mean radiant temperature cause the heating demand to rise. The cooling demand remains on low level in Munich. The results for Madrid show a similar trend with this control strategy. More drastically is the cooling demand changing in Dubai, where the demand is rises above that of all other control strategies. Again, it is assumed that the clothing insulation and the mean radiant temperature cause the demand for higher cooling power to rise, since the number of hours of cooling is approximately the same as with the control strategy CS3. This also explains why the electricity demand for lighting is on the same level as with the control strategy CS4.

2.5. Control strategy CS5

The control strategy CS5 provides a less high level of comfort compared to the control strategy CS4. As a result, the heating demand is the lowest in Munich compared to the other control strategies, which is because of fewer hours when heating is required. A less high level of comfort also reduces the heating demand in Madrid considerably, but the cooling demand remains on the level of the control strategies CS2 to CS5. The cooling demand declines with this control strategy in Dubai even more drastically than in Madrid. Although the number of hours in CS4 and CS5 are almost the same, the power demand for cooling is lower in CS5.

3. Conclusion

This paper studies a new type of glazing, which is titled Fludglass. This glazing allows circulating fluid in chambers of the glazing. Increasing the concentration of a colorant can change the transmittance of the glazing. The studied models set the colorant concentration according to different control strategies. As expected, the control strategy considerably determines the success of the Fluidglass element. This paper only studies the effect that changing the colorant concentration of the exterior Fluid chamber has on the heating-, cooling and electricity demand for lighting. Other controls of this new type of glazing, which are fluid inlet temperatures and mass flow rate, have not been studied. In general, the results of the studied control strategies show that Fluidglass can reduce the cooling and heating demand at all three different locations compared to a reference building with good solar glazing.

The model designed for this study simplifies the complex interaction of the Fluidglass and is based on certain assumptions, which need to be verified during the development of the Fluidglass-project. This model proves that control strategies considerably account for the efficiency of the Fluidglass system. Simply strategies that only consider the solar irradiation based on normative standards (CS1) allow for a high reduction of the cooling demand, which is beneficial in Dubai and partly in Madrid, but can cause the heating demand to rise at locations like Munich, because of lower passive heat gains. More successful are control strategies that also consider the interior air temperature (CS3, CS4, CS5). They allow in Munich for a reduction of about 20-30% and a reduction of the electricity demand for lighting of about 20%. The same type of control strategies reduce the energy demand for heating and cooling in Madrid drastically of about 50-70%, but cause the electricity demand for lighting to rise by 10-20%. Even more unbalanced is the energy reduction with this type of control in Dubai with an energy reduction of about 50-60% for cooling, but an drastic quadruplicating of the electricity demand for lighting. In summary, energy reduction in cooling and heating demand need to be balanced with potentially rising electricity demand for electrical lighting. This can only be answered in context of a building- and lighting system.

At this stage of research, none of the studied control strategies shows to be optimal for all climate conditions to achieve highest energy reductions. Further research is necessary in the development of a control strategy that can universally be applied to not ensure lowest heating, cooling and electricity demand, but also to allow for a reasonable level of comfort. Furthermore, all the studied controls are rule based and do not include predictive strategies. There is some expectation that Fluidglass can be operated with predictive controls more efficiently, since the transmittance of the glazing can quickly be changed.

4. Acknowledgement

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