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A workflow for retrofitting façade systems for daylight, comfortable and energy efficient buildings

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Abstract. The building façade not only provides the aesthetic signature of a building, but also important functions, such as daylight provision, glare protection, solar gain management and visual contact with the outside, which make the building usable and energy efficient. These functions often oppose each other, so the selection and design of façade systems and their control for a certain building application should depend on those functions that the designer wants to promote to the detriment of the other functions. In the context of the H2020 RenoZEB project, this paper presents a workflow for the conceptual planning of façade systems as applied to building retrofitting. The proposed workflow consists of analysing the space from the point of view of the functions of its façade. In a first step, the analysis of the case study leads to the definition of the design requirements, i.e. the relevance of the different façade functions and their priorities. The second step involves the selection of a suitable fenestration system and control strategy for the retrofit solution. In this step, an optimization process for the control strategy is proposed based on state-of-the-art thermal and daylighting simulations. In a third step, the annual performance of the retrofit solution is evaluated in order to check if the requirements are fulfilled. The proposed workflow is illustrated with a case study, in which the automation strategy of a retrofitted façade system is optimized for two different applications: a residential and an office building in Bilbao (Spain).

Keywords: retrofit, façade, comfort, energy efficiency, building simulation, daylight.

1. Introduction

The building façade is in charge of important building functions for its occupants, such as visual contact with the outside, daylight provision, glare protection, solar gain management, security and privacy. Movable shading devices or switchable elements are necessary in order to dynamically balance the different façade functions, which are of varying relevance, depending on the time of the day and season. This implies the consideration of a control strategy. Several studies show that manual control is neither optimized in terms of energy efficiency nor in terms of comfort. Building occupants generally close a shading system to prevent direct solar radiation but then forget to retract it [1].

Commercial automatic control of fenestration systems, on the other hand, often consists of an on/off strategy activated on the basis of an outdoor illuminance sensor installed on the rooftop or an indoor luminance meter on the ceiling in order to estimate workspace illuminance [2]. Numerous studies have shown that these control systems have low occupant acceptance [3]. User dissatisfaction might be caused by the lack of consideration of all (or at least the most important) facade functions in the control strategy.

Nevertheless, control strategies for façade systems are attracting increasing attention in the context of room automation systems and smart-buildings. Modern room control units give the user direct access to the room temperature set point, the lighting control and the control of the shading system through smartphones and tablets applications.

Innovative control strategies for façade systems may depend on thermal and daylighting variables. These can be measured by a set of sensors in the room or dynamically calculated by simulations [4]. The controlling variables and their priority must be chosen depending on the façade functions to be promoted. Example of controlling variables are the occupation, time of the day, the day of the year, the indoor and outdoor air temperatures, the exterior solar irradiance on the roof/at the façade, as well as horizontal and vertical illuminances.

This paper presents a workflow for the conceptual planning of façade systems that can be applied to different tertiary and residential buildings. The proposed workflow consists of analysing the space from the point of view of the functions of its façade and then selecting a suitable fenestration system and control strategy based on state-of-the-art building simulations. The steps of the workflow are shown in figure 1.

In this study, the proposed workflow is illustrated by a case study. This consists of two west-oriented rooms in Bilbao (Spain) with two different uses: an office and a residential apartment. Both buildings share the same existing and retrofit fenestration system. The case study focuses on how to optimize the control strategy of a room automation system for each application, office and residential, based on state-of-the-art thermal and dynamic simulations.

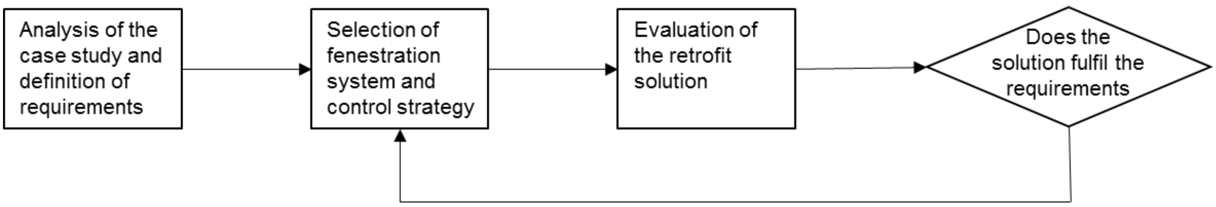

Figure 1. Diagram of the proposed workflow for retrofitting façade systems.

2. Analysis of the case study and definition of requirements

The first step of the proposed workflow is to analyse the case study in order to determine its requirements for the façade, i.e. the relevance of the different façade functions for the particular case study.

In order to define specific requirements for the façade system, the different façade functions must be quantified with metrics. This poses a specific problem, because some functions are easier to quantify than others. For example, numerous studies have shown that the daylight autonomy is a good metric for the evaluation of dynamic daylighting [5], but a commonly accepted metric for the view contact with the outside does not exist. Another example is the quantification of glare protection. Dynamic glare is still very difficult to quantify, requiring detailed characterization of fenestration systems and costly computation capacity. A suitable set of metrics for a specific case study depends on the scope of the analysis and on the preselection of fenestration systems. The metrics that can be used to quantify the different facade functions are summarized in table 1.

Table 1. Metrics for different façade functions. The list is not exhaustive. There can be other functions.

Function	Metrics
Visual contact with the outside	Direct-direct transmittance in the visible spectral range above a threshold (e.g. 3%)
Glare protection	Percentage of occupied hours with Daylight Glare Probability index [6] below a threshold (e.g. 0.45) Same as previous but using the vertical illuminance (e.g. 3500 lux)
Daylight provision	Percentage of occupied hours with average horizontal illuminance above a threshold (e.g. 300 lux) Daylight Autonomy Annual energy demand for electric lighting
Thermal comfort	Percentage of occupied hours with PMV within a range (e.g. from -1 to 1) Mean Predicted Mean Vote (PMV) Mean Predicted Percentage Dissatisfied (PPD)
Solar heat gain management	Annual energy demand for heating Annual energy demand for cooling
Aesthetics	No accepted metric
Privacy	Direct-direct transmittance in the visible spectral range below a threshold (e.g. 0.1%)

3. Selection of a fenestration system and control strategy

Weighting the different façade functions for each studied room is followed by a selection of suitable façade systems. Considerations such as exterior, in-between glazing or interior, fixed or retractable shading devices, the type of shading device (e.g. roller shutters, roller blinds or venetian blinds), as well as the properties of the shading device and glazing unit, must be taken at this stage. In addition, a control strategy for the shading device must be selected, starting by choosing between purely manual control and manual control combined with automatic features.

The performance of a switchable fenestration system is entirely dependent on the control strategy. The control strategy should maximize the hours of uncovered façade and thus to benefit from the outside views. At the same time, for the hours when the façade is covered, the control strategy must allow a certain contact with the outside. In addition, the system must preserve a glare-free space, it must maximize daylight as much as possible and it must reduce the heating and cooling energy demand of the room, or alternatively influencing positively the thermal comfort of the room.

The design of the control strategy consists of establishing the priorities among functions and defining the setpoints for each of these metrics. This can be achieved by using dynamic building simulations. The Fener simulation engine [7], developed at Fraunhofer ISE, offers the possibility to easily compare different fenestration systems and control strategies in terms of daylight provision, glare protection and energy demand. Fener is a building program based on the three-phase method [8] and a detailed energy balance of one room. It calculates simultaneously the heating and cooling energy demand of the room, thermal comfort metrics, daylighting metrics and daylight glare indexes.

4. Evaluation of the retrofit solution

The last step of the proposed workflow is to evaluate the performance of the retrofit solution compared to the existing scenario through dynamic thermal and daylighting simulations. The simulation tool must be able to calculate the metrics defined in the first step of the workflow. Based on the simulation results, the fulfilment of the requirements by the new retrofit solution can be checked and, eventually, changes to the retrofit solution can be further evaluated.

5. Case study

A case study is presented to illustrate the proposed workflow. This example focuses on the optimization of the control strategy of a facade system for an office and a residential building in Bilbao (Spain). Table 2 summarizes the boundary conditions of the two applications.

Table 2. Boundary conditions of the office and residential rooms considered in the case study. LT refers to local time and ACH refers to air changes per hour. Internal heat gains refer to square meters of floor area.

Building type	Office	Residential
Location	Bilbao	Bilbao
Orientation	West	West
Glazing ratio	80%	40%
Working hours	8-18 LT (weekdays)	18-8 LT
Infiltration/ventilation	0.6 ACH / 0.2 ACH	0.5 ACH
Internal heat gains	15 W m^{-2}	10 W m^{-2}
Cooling thermal setpoint	26 ◦C	None
Heating thermal setpoint	20 ◦C	20 ◦C
Construction type	Heavy	Heavy
U-value of external wall	0.2 W m^{-2} K^{-1}	1.7 W m^{-2} K^{-1}

Table 3. Summary of the results of the analysis of the case study.

Requirement	Metrics (Office)	Metrics (Residential)
Daylight provision	Percentage of occupied hours with average horizontal illuminance above 300 lux	Percentage of occupied hours with average horizontal illuminance above 300 lux
Glare protection	Percentage of occupied hours with maximum vertical illuminance below 3500 lux	Not relevant for residential buildings
Solar heat gain management	Heating energy demand Cooling energy demand	Heating energy demand Mean PMV for thermal comfort
View contact with the outside	Not evaluated	Not evaluated

Both applications, office and residential, are west oriented and have the same fenestration system. The fenestration system consists of an insulating double-glazing unit and vertical interior textile blinds. Given the location and the dimensions of the room, the transmittance of the blinds is sufficient

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to provide enough daylighting in the room during the central hours of the day for the office room. However, the interior blinds cannot prevent high solar heat gains in the afternoon, which produce a high cooling energy demand in the case of the office and thermal discomfort in the case of the residential room. The originally installed vertical blinds can be manually rotated or fully retracted. In both cases, the occupants tend to constantly leave the blinds closed in order to prevent high irradiation levels on the façade in the afternoon and to provide privacy in the case of the residential room. The fact that the blinds are constantly closed due to an inconvenient manual control prevents the occupants from enjoying outside views. Additionally, the used roller blind material prevents any contact to the outside when the blinds are closed.

Based on the analysis of the case study, the requirements of the retrofit solution are summarized in table 3.

In both cases, the chosen fenestration system for retrofitting is an exterior roller blind with an outer reflective surface. Exterior shading devices are much more effective to prevent solar heat gains than interior ones. The chosen textile has an openness coefficient (normal-normal transmittance) that allows a view through the textile material, which the original material did not. The openness coefficient is small enough to prevent glare when the blind is closed.

Table 4. Control algorithms of the façade system written in pseudo-code. The setpoints SP1, SP2, SP3, SP4 and SP5 are calculated through an optimization process.

Office	Residential
if occupation:	if occupation:
if average_workplane_illuminance>SP2:	if average_workplane_illuminance>SP5:
if indoor_air_temperature>SP1:	if indoor_air_temperature>SP4:
or	CLOSE
max_vertical_illuminance>SP3:	else:
CLOSE	OPEN
else:	else:
OPEN	OPEN
else:	else:
OPEN	if daytime:
else:	if indoor_air_temperature>SP4:
if daytime:	CLOSE
if indoor_air_temperature>SP1:	else:
CLOSE	OPEN
else:	else:
OPEN	if indoor_air_temperature>SP4:
else:	OPEN
if indoor_air_temperature>SP1:	else:
OPEN	CLOSE
else:	
CLOSE	

Two shading control algorithms, one adapted to the office case and one adapted to the residential case, were developed to optimize the functions of the fenestration system (table 4). For both of the algorithms, when the room is unoccupied, the algorithm compares the measured indoor temperature with a temperature setpoint in order to decide whether to activate the shades during day blocking solar heat gains or to deactivate them during night enhancing heat transfer through the window. When the room is occupied, a minimum daylighting level must be reached before the shade is closed. Once the daylight condition is fulfilled, the algorithm checks the indoor air temperature for both the office and the residential rooms. Additionally, the algorithm for the office also checks the maximum vertical illuminance to prevent glare. For the residential case, glare protection is not considered as a requirement. If any of these variables reaches a certain threshold, the shades are activated.

An optimization process is setup in order to obtain the setpoints of the control algorithms. The Fener tool [9] is used to compare scenarios with different setpoints. The metrics used to compare scenarios for the office case are the following: the percentage of occupied hours where the average horizontal illuminance is above 300 lux (daylight provision), the percentage of occupied hours where the maximum vertical illuminance is below 3500 lux (glare protection), the heating energy demand and the cooling energy demand (solar heat gain management). For the residential case, the metrics used to compare scenarios are the following: the percentage of occupied hours where the average horizontal illuminance is above 300 lux (daylight provision), the heating energy demand and the mean PMV for thermal comfort (solar heat gain management).

Table 5. Results of the optimization process for the office. SP1 refers to a temperature setpoint (^{o}C). SP2 and SP3 refer to illuminance setpoints (lux). The selected setpoints correspond to case 4.

Cases	SP1 (°C)	SP2 (lux)	SP3 (lux)	Occupied hours of daylighting	Occupied hours without glare	Heating Demand [kWh m-2 year-1]	Cooling Demand [kWh m-2 year-1]
1	23	300	3200	65%	95%	9	17
2	23	500	2760	66%	93%	10	21
3	24	500	3500	66%	93%	10	21
4	25	300	3500	68%	95%	9	17

Table 6. Results of the optimization process for the residential room. SP4 refers to a temperature setpoint (°C). SP5 refers to an illuminance setpoint (lux). The selected setpoints correspond to case 2.

Cases	SP4	SP5	Occupied hours of Daylighting	Heating Demand [kWh m-2 year-1]	Mean PMV
1	23	300	10%	3	0.7
2	23	500	12%	3	0.8
3	25	400	11%	3	0.8
4	26	400	11%	3	0.9

The results of the optimization process for the office and residential cases are shown in table 5 and 6, respectively. The selected setpoints to be used in the control algorithms are the ones corresponding to case 4 for the office case and to case 2 for the residential case.

To evaluate the retrofit solution as compared to the existing baseline scenario, dynamic simulations are run with the Fener tool under the boundary conditions indicated in table 2. In the baseline scenario, the original interior blinds are fully closed all the time. In the retrofit scenario, the proposed roller blinds are activated according to the control algorithms described above. Figure 2 shows the heating, cooling and lighting energy demands for the baseline and retrofit scenarios of the office (left) and of the residential room (right). For the office case, by taking only the occupied hours, the results indicate that the application of the exterior roller blind would result in an important reduction of cooling energy demand (63%). For the residential case, the results indicate that the application of the exterior roller blind would result in a reduction of both heating energy demand (13%) and lighting energy demand (58%).

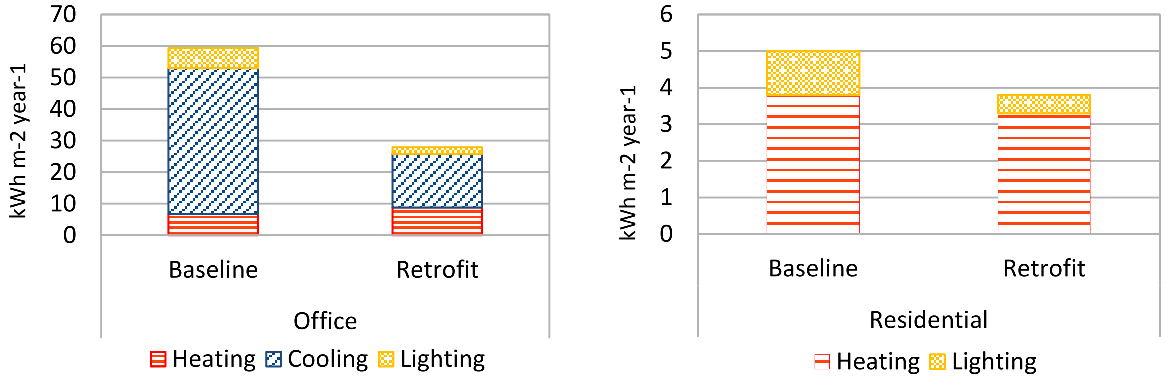

Figure 2. Heating, cooling and lighting energy demands of baseline and retrofit scenarios of the office and residential cases.

The thermal comfort of the occupants of the residential case appreciably improves with the new fenestration system and control algorithm. The mean PMV of the baseline and retrofit scenarios for the residential room is shown in figure 3 on a monthly basis. PMV values are closer to the optimal state (PMV = zero) in the retrofit scenario.

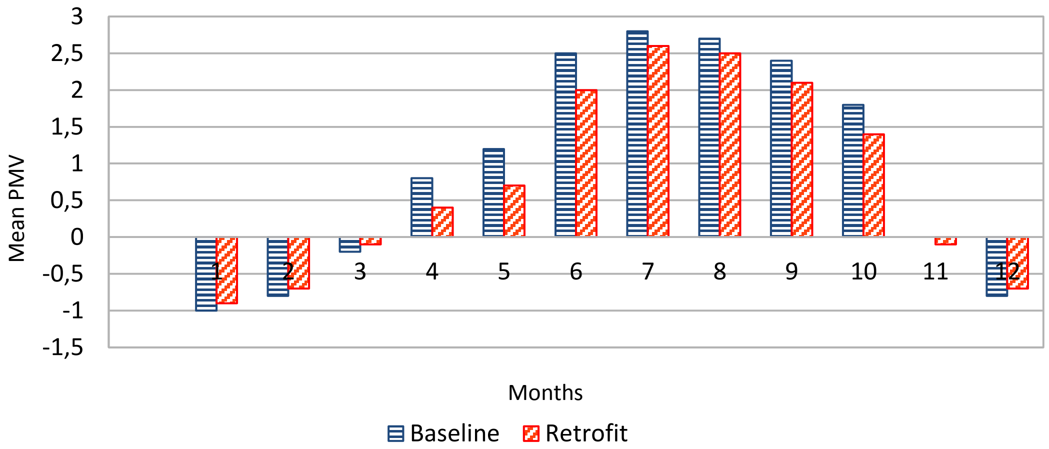

Figure 3. Predicted Mean Vote (PMV) of thermal comfort for the baseline (blue) and retrofit (red) scenarios for the residential case.

In terms of the daylighting and visual comfort, the retrofit solutions improve the daylight provision from 20% to 68% for the office room and from 1% to 12% for the residential room. For the residential case, it should be noted that the occupied hours are the early and late hours of the day. On the other hand, the percentage of occupied hours without glare decreases from 100% to 95% for the office room. The number of hours with unobstructed views to the outside significantly increases with the new control strategy.

6. Conclusions

In this study, a workflow for the conceptual planning of façade systems as applied to building retrofitting has been presented. According to this workflow, the design of the façade system must be carried out first at room level. Once the façade solutions for the individual rooms are analysed, a harmonized solution at building level can be determined, which must then be re-tested at room level. The workflow consists of analysing the level of importance of the different functions of a façade for a particular application and then applying automated control and building simulations to optimize the design. The functions analysed in this case study are visual contact with the outside, daylight provision, glare protection, solar heat gain management, but other functions such as burglary protection and privacy can also be included.

The proposed workflow is illustrated through a case study in Bilbao (Spain). The case study consists of two west-oriented rooms with different uses: office and residential. Two different shading control strategies for the room automation system are designed for the office and the residential rooms. As a result, the energy demand for cooling is significantly reduced in the office room and the thermal comfort increases in the residential room. In addition, the occupants have more hours of undisturbed view contact with the outside and better daylighting than in the baseline scenario.

The study highlights the need to take into account the multifunctional nature of building façades in the design of retrofitting solutions. It also show how advanced building simulations can be used very targeted to assists in different stages of the design process without replacing expert decision making by the designer.

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