A Review on the FIVA-Project: Simulation-Assisted Development of Highly-Insulating Vacuum Glass Windows

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Abstract

This contribution provides a review on research and development activities that have been conducted in the field of highly-insulating windows with vacuum glass. In a joint effort with the window-producing industry, different novel solutions for vacuumglass-equipped windows have been studied. Thereby, different methodological approaches have been deployed, including the construction of technology demonstrators, performance measurements on laboratory test sites, and numeric thermal bridge simulation. As a result, the project consortium succeeded in the development, construction, and exhibition to relevant stakeholders in the industry of four, innovative window prototypes. These windows not only employ vacuum glass products, but also in part provide new operation kinematics, motorization, and the implementation of automated ventilation positions. Moreover, the U-values of the windows could be approximated to be around or below 0.70 $W.m^{-2}.K^{-1}$ (i.e., U_{Win}-value) at pane thicknesses of less than a centimeter. The windows include turn windows to inside and outside, as well as a swing-operation window, and a window utilizing an offset- and slide-operation mechanism without visible railings. The contribution not only displays the final prototypes, but also highlights the methods and provides an outlook for future development in this area.

1. Introduction

1.1 Scope of the FIVA Project, Observations and Prerequisites

The present contribution highlights the methodology and results of a joint research effort conducted together with stakeholders of the window producing industry. The ultimate goal of this project, which was named FIVA (*Fensterprototypen mit integriertem Vakuumglas* – in English: Window prototypes that employ vacuum glass) was the development of vacuum-glazing-equipped windows that provide both a very good (thermal) insulating performance and a high degree of innovation in architectural appearance and operation. Moreover, that the resulting prototypes should fully prove their functionality, or in other words, a high TRL (technology readiness level) of the envisioned prototypes was an additional planned goal of the project.

The project's outline was built on and started based on a set of observations (O) and prerequisites (P):

O(bservation)1: Although vacuum glass products finally arrived on the market after intensive research and development efforts by both industry and academia lasting close to a century (Zoller, 1913), there was little to no public and relevant research available about the utilization of such products in contemporary and past window constructions. **O2:** Companies in the window-producing sector agreed about the high potential of vacuum glass for window constructions, however, most companies were reluctant to pioneer vacuum-glazed window constructions. Moreover, there was little knowledge about the required changes to existing window/frame constructions amongst the relevant stakeholders. Furthermore, resentment against vacuum glass pertaining to the durability of the vacuum (and thus its thermal performance) in the products was reckoned. Given that, until 2020, vacuum glass products were not produced in

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Europe, but majorly in South-East Asia, another threat was seen in the long delivery times in the case of the need for glass replacement. Moreover, while there have been multiple producers of multi-pane insulation glass, the number of vacuum glass producers was (and still is) limited. **O3:** Stakeholders in the glass-producing industry showed a certain ambivalence toward vacuum glass products. This was majorly because vacuum glass products show similar thermal performances to high-end triple glazing, but do feature one glass pane less (which would potentially have negative effects on feasibility and profit for glass producers). **O4:** Despite major efforts toward improvement of the performance of transparent envelope components, windows are still considered the weak spot in thermal envelopes, and are even considered to be responsible for a major share of building-related energy loss through the envelope. However, current highly-insulating windows are majorly triple-glazing windows coming with large system thickness and correspondingly heavy weight of the overall construction. Vacuum glass is considered to disrupt this situation.

Amongst the prerequisites for the FIVA project were the following: **P(requisite)1:** basic knowledge about the durability and thermal performance of different vacuum glass products was required. This was fulfilled due to the authors' previous research efforts into vacuum glass within the VIG-SYS-RENO project (Pont et al., 2018a). In this exploratory product, not only a wide range of tests pertaining to mechanics, thermal performance and acoustical performance of different glass products was conducted, but also basic challenges pertaining to the integration of vacuum glass into existing and new window frames were addressed. **P2:** A clear objective is required in the development process. While the integration of vacuum glass in existing (historically relevant) windows often needs to consider the upkeep of the appearance of the window (e.g., Kastenfenster / casement windows, compare (Pont et al., 2018b), new windows can be designed toward performance and operation optimization. Moreover, the specifics of vacuum glass (e.g., problematic thermal bridge along the edge seal) determine construction principles. As such, it was decided to design the windows from scratch based on the specific requirements of the vacuum glass, rather than to adapt existing window constructions. **P3:** Subsequently, a set of innovative early-stage window designs (that consider the specifics of vacuum glass) was required. Such innovative and, in part, disruptive approaches to new windows were the result of another preliminary and exploratory research effort by the authors named MOTIVE (Pont et al., 2018c). **P4:** To start and successfully conduct the project, a strong consortium of academic partners and stakeholders from the relevant branches of industry was required who were open to new ideas and agreed upon close collaboration. This consortium consisted in the end of two academic and eight industrial partners (5 window-producing companies, 3 producers of different window constituents, namely fittings, seals, and vacuum glass). **P5:** To be able to explore the space of potential, innovative, high-performing vacuum glass windows, all partners were required to bring in their specific expertise and instruments. Simulation as a method specifically was deployed in the fields of operation kinematics of the innovative windows, and thermal performance assessment. For the latter, numeric thermal bridge simulation was deployed as instrument of choice.

1.2 Vacuum-Glazing Products

To understand the challenges connected with the integration of vacuum glass in windows, one needs to understand the technical specifications of vacuum glass. Vacuum glass products are regularly constituted of two planar, parallel glass panes. Between the glass panes, an interstitial space of rather small dimension (less than a millimeter) houses a grid of distance pillars. The axis-distance between the pillars is regularly between 20 and 40 mm. To close the interstitial space against the surroundings, a vacuum-tight edge seal is set up along the perimeter of both glass panes. Via an opening in one of glass panes, the interstitial space is then evacuated (leading to a high vacuum). The distance pillars mentioned maintain the parallel position of the glass panes, as otherwise the panes would be pushed together by the surrounding air pressure. Another important element is the socalled getter. This is a highly reactive surface that filters/binds the remaining particles in the interstitial space. Due to the vacuum, heat transfer processes that require media are widely eliminated in the interstitial space (i.e., conduction and convection). Thereby, already rather slim systems (vacuum glass between 6 and 8 millimeters) provide excellent thermal insulation. However, the glass-edge seal, as well as the distance pillars, literally remain as connecting thermal bridges between the two glass panes and need to be considered in designing windows with vacuum glass. In a previous research effort (Pont & Mahdavi, 2017), the heat loss via conduction through the pillars was identified as noticeable but very small (majorly due to their limited physical dimensions). In contrast, the tight edge seal was identified as a major thermal bridge and needs to be covered / insulated as well as possible in window constructions. A sufficient glass edge-cover length can ensure this. Fig. 1 illustrates a schematic section through a (generic) vacuum glass product.

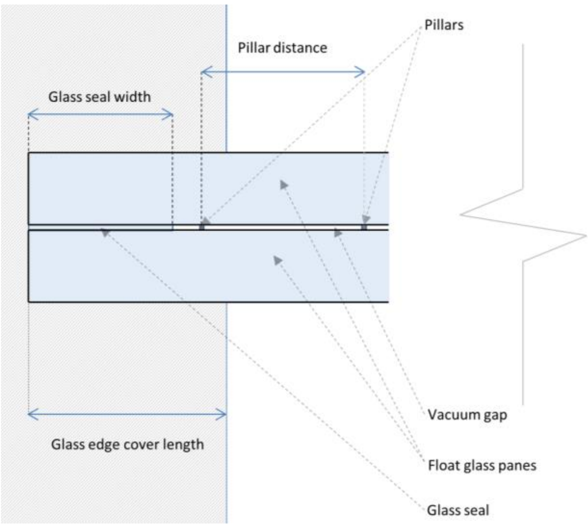


Fig. 1 – Schematic section through a generic vacuum glass product, including the relevant terminology (illustration by the authors)

2. Methodology

2.1 General R&D Efforts Within the Project

The development of new windows requires considerations from different backgrounds. Aspects such as the statics, weight, operation, acoustics, thermal performance, material, form and construction of frames, fittings, glass, seals, and many more need to be considered. To comply with these in part harsh requirements, the following strategy was deployed: in a first attempt, the major aspects to be worked upon were identified, including shifting certain aspects to post-project phases (as final product development done by the industry). Such aspects included production aspects, or the selection of the final components. Rather, the project team decided to work upon three major aspects: (a) The conception of specific window prototypes as such, which includes the operation/movement patterns and the principle architectural appearance. (b) The integration of motorized fittings for the specific window, preferably to be integrated in the fixed window frame (not into the moving part of the window. (c) The integration of the vacuum glass in the moveable wing of each of the windows under consideration of specific requirements of the vacuum glass, such as a well-dimensioned glass-edge seal cover. After setting up a decision fine-tuning of these aspects, an iterative development process started. Thereby, for each of the window prototypes, one of the industrial partners assumed responsibility for development, thus constructing the early prototypes and movement mock-ups, and conducting communicating/coordinating of geometry and semantic data means of their prototype with the consortium. The scientific partners, together with the industrial partners, were continuously developing and designing the corresponding windows. Thereby, one of their major responsibilities was to deliver proof of concept and proof of functionality results. A lot of iterative optimization characterized this later stage of the development. This workflow worked well and offered a lot of productive exploration of the space of possible solutions, mostly due to the many brainstorming and sketching meetings that were set up regularly.

2.2 Simulation and Thermal Performance Assessment

As already mentioned, one of the key tasks of the scientific partners in the project (namely the authors of this contribution) was to continuously assess the impact of design modifications on the thermal performance. To this end, we deployed numeric thermal bridge simulation as matter of choice in assessing the critical thermal bridge situations along the window frames and highly conductive fitting parts. The tool we used was Antherm v. 10 (Antherm n.d.).

Moreover, the overall performance of the window in view of thermal transmittance was evaluated. Due to the non-off-the-shelf character of the windows, the equations from corresponding standards (i.e., EN ISO 10077 Parts 1 and 2 (EN10077 2017)) were found to be inappropriate for the purposes of vacuum glass windows, and thus slightly adapted. This majorly affected the U_{Win}- equation, in which parts of the frame geometry that were supported with the highly-insulating vacuum glass were considered specific parts of reduced heat transfer in contrast to the otherwise rather weak performance of the frame.

Tables 1 and 2 illustrate both assumed conductivities and boundary conditions that were used for thermal performance assessment. Note that for encapsulated air and the vacuum gap replacement, Lambda-Values were considered, and that the colors in the table correspond with the materials in the illustrations in the Results section.

2.3 Subjective Assessment of Window Prototypes

To ensure that all relevant stakeholders accept new window constructions, it is not sufficient to just promise and provide excellent performance values. Rather, relevant stakeholders need to be convinced about aspects such as aesthetics, contemporaneity, innovation, feasibility of the construction, aspects of mounting, aspects of operation, and general acceptance amongst customers. To collect the opinion of domain experts and non-experts, we developed a short and easy-to-use questionnaire that encompassed these categories and allowed them to be graded (by the Austrian school grading system, starting from excellent to insufficient). Additionally, windows could be ranked by preference in the questionnaire, and additional comments could be written in the questionnaire.

Table 1 – Assumed thermal conductivities of materials and replace materials (vacuum gap, encapsulated air)

Color	Material	Conductivity [$W.m^{-1}.K^{-1}$]
	Timber / Wood	0.11
	Steel	50
	Aluminium	200
	Compac Foam	0.031
	Insulation	0.041
	Seal(ing)	0.3
	Seal encapsuled	0.04
	Glass	1
	Plastic	0.2
	Masonry	0.45
	Purenite	0.096
	Plaster	0.7
	Silicone	0.35
	Vacuum	0.00000975
	Encapsulated Air	0.07

Table 2 – Boundary condition settings.

Colour	Boundary Condition	Rs (H,T) Value [$m^2.K.W^{-1}$]
	Inside	0.13
	Outside	0.04

3. Results

3.1 Developed Window Prototypes

In the project, four different window prototypes were worked upon in depth and finally realized as full-scale functional mock-ups. These were:

- Turn window opening to inside (A): while adopting the traditional, established operation scheme of central Europe, the window provides a glass-inline-with-outer-perimeter appearance. Integration of external shading is easy, and the window operation is widely familiar to users.

- Turn window opening to outside (B): while not common in Central Europe anymore, windows that turn to the outside are familiar in Scandinavia. B comes with a rather reduced and thus aesthetically pleasing appearance.
- Swing window (C): adopting the principles of garage doors, this window provides a rather convenient way of storing the open wing above occupants' heads and thus allows spatial flexibility. The window was engineered to possess maximum flexibility and as few moving parts as possible.
- (Offset and) Sliding window (D): this window allows an offset movement to the outside for the purpose of ventilation. From this position, the window can be slid to one side on telescope railings, which remain totally invisible when the window is in its closed state.

All of the windows were equipped with electrical actuators, so that motorized operation could be realized. Thereby, automated operation in most cases covered the shift from fully closed to a ventilation position, while the classical full opening was still to be carried out manually (however, this has to be understood as a suggestion, both fully manual and fully motorized operation is possible in all four of the prototypes).

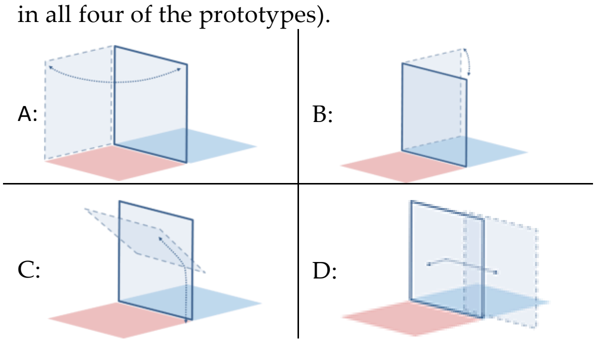


Fig. 2 – Opening/operation schemes of prototype A – D.

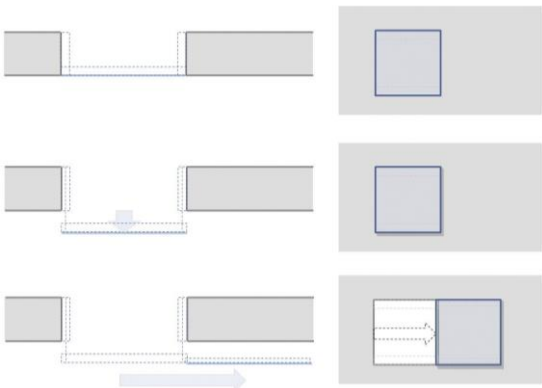


Fig. 3 – Conceptual view and section of prototype D

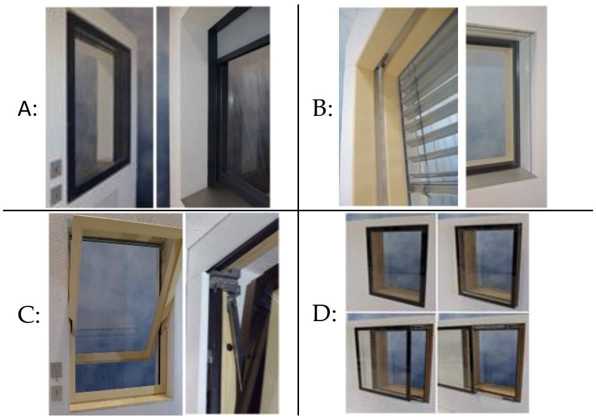


Fig. 4 – Opening/operation schemes of prototype A – D.

Fig. 2 illustrates the opening scheme of all four windows, while Fig. 3 provides some additional insight into prototype D. Fig. 4 shows photos of the finalized prototypes.

3.2 Performance Aspects of Developed Windows

A full documentation of the conducted thermal performance simulation efforts can be found in (Wölzl, 2019) and (Pont et al., 2020a). Exemplarily, Tables 3 to 6 illustrate some Key Performance Indicators (KPIs) of both the windows and the most crucial building construction joint, which is the lower connection between wall and window. The presented KPIs encompass U_{Win}-value, as well as f_{Rsi}-values and minimum surface temperature $\theta_{min,i}$. Note that the latter KPIs have been simulated assuming steady-state boundary temperatures (external temperature of -10 °C, internal temperature 20 °C). The tables always provide the same structure: KPIs on top, followed by a false color image denoting the temperature distribution within the mentioned construction joint, and section through the same joint highlighting the assumed materials (compare Table 1 and 2).

Table 3 – Thermal Simulation of Window A

Turn window opening to inside (A)
f_{Rsi} 0.74 [-] ǀ $\theta_{min,i}$ 12.23 °C ǀ U_{win} 0.78 $W.m^{-2}.K^{-1}$

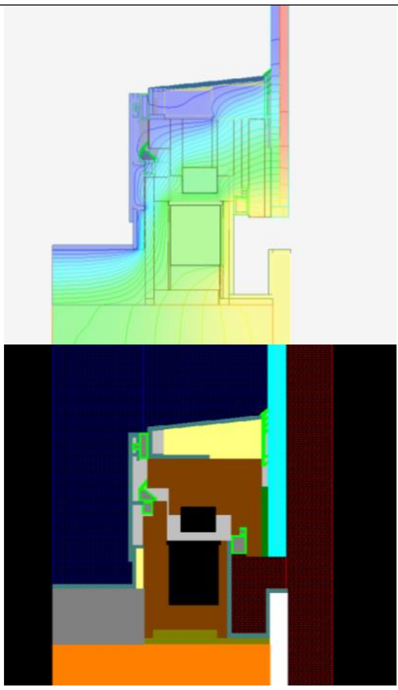


Table 5 – Thermal Simulation of Window C

Swing window (C)
f_{Rsi} 0.75 [-] ǀ $\theta_{min,i}$ 12.55 °C ǀ U_{win} 0.68 $W.m^{-2}.K^{-1}$

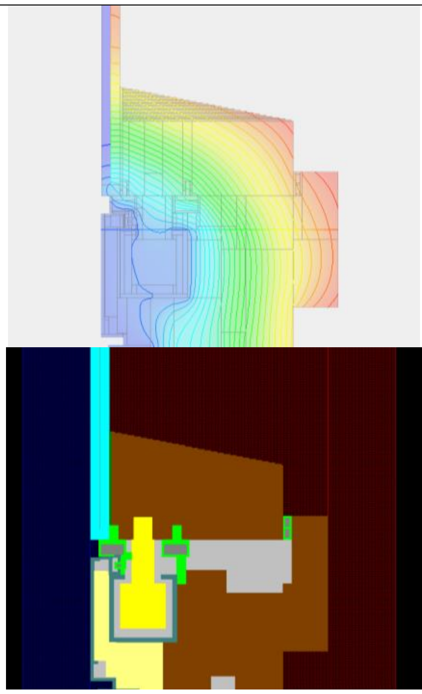


Table 4 – Thermal Simulation of Window B

Turn window opening to outside (B)
f_{Rsi} 0.77 [-] ǀ $\theta_{min,i}$ 13.05 °C ǀ U_{win} 0.72 $W.m^{-2}.K^{-1}$

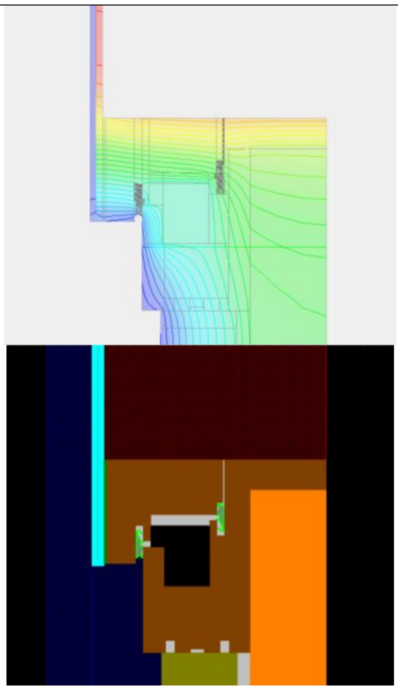
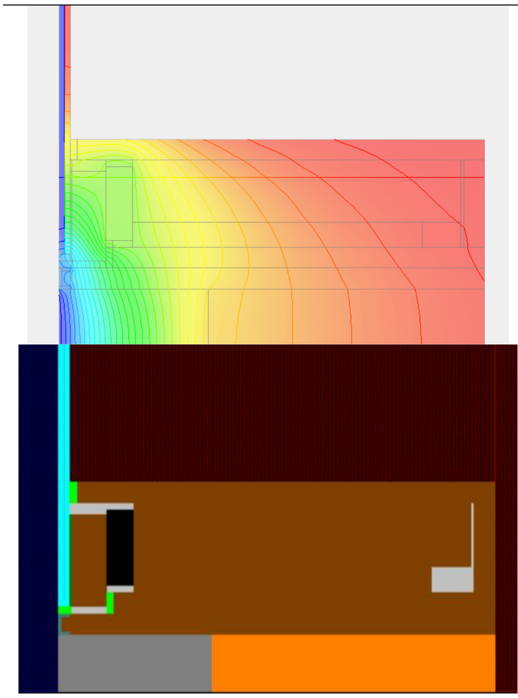


Table 6 – Thermal Simulation of Window D

Sliding window (D)
f_{Rsi} 0.76 [-] ǀ $\theta_{min,i}$ 12.07 °C ǀ U_{win} 0.64 $W.m^{-2}.K^{-1}$



Note that for all of these window prototypes, a vacuum glass pane of 8.15 mm thickness was assumed (U_g-value 0.7 $W.m^{-2}.K^{-1}$). The presented KPIs of all of the window prototypes well surpassed the minimum criteria for condensation risk assessment (which is a threshold f_{Rsi}-value of 0.71 following typical standards for opaque building constructions). Moreover, the U_{Win}-values that were reached are in the range of heavyduty triple glazing windows. Needless to say, the window constructions presented are featherweights in comparison with the triple-glazing windows mentioned.

3.3 Subjective Evaluation of Window Prototypes

The questionnaire-based evaluation of the prototypes was conducted during the FTT2020 (Fenster Türen Treff, 2020) in Salzburg, which is a trade fair and knowledge exchange event of the domain-relevant industry. All four window prototypes were exhibited there, and a talk about the project was held (Pont et al., 2020b). Fig. 5 shows the window prototypes in the exhibition. The grading results of the questionnaire are summarized in Table 7. Pertaining to the question as to which of the windows was preferred by the respondents, results showed that window D was favored, closely followed by A. This can be considered interesting, because these windows are fundamentally different: window D provides a disruptive new design with a very innovative and aesthetically attractive appearance and operation, and is thus far from what we see in most contemporary buildings. Prototype A, in contrast, is the contemporary adaptation of a well-established traditional window operation scheme. The rating by the domain experts thus hints at the fact that both tracks - disruptive change and continuing traditional technologies – need to be followed up.

Fig. 5 – Window prototypes exhibited during FTT2020 (Salzburg)

Table 7 – Domain experts' evaluation of the window prototypes (Austrian school grades: 1… excellent, 2… good, 3…average, 4… sufficient, 5…insufficient)

Criterium	A	B	C	D
Esthetics	1.7	2	2.4	1.2
Contemporaneity	1.8	2,4	2.6	1.6
Degree of innovation	2.1	2	2.2	1.2
Feasibility of the construction	1.8	2.4	2.6	2.1
Aspects of mounting	1.8	2.4	2.2	2.4
Aspects of operation	1.7	2.4	2.5	1.7
Acceptance amongst customers	1.9	2.4	3	1.8
Average	1.8	2.3	2.5	1.7

4. Conclusion and Future Research

The present contribution illustrated the outcome of a collaborative R&D effort which emphasized a set of interesting aspects:

- Shared projects between the building industry and academia can lead to disruptive developments in the AEC-context. Given the Paris climate goals and the rather slow innovation processes in the built environment, we are in urgent need of such fast-forward developments.
- The design of vacuum-glass-equipped windows should be carried out from scratch, even if traditional window operation concepts such as "turn-to-inside" are deployed. It is not feasible to simply take existing frame constructions and replace multi-pane insulation glass with vacuum glass, as such constructions cannot regularly fulfil the specific requirements of vacuum glass, such as a sufficient glass edge-cover length.
- While the window wing should be constructed around the vacuum glass, it seems wise to construct the fixed part of the window frame around the fittings system. As such, motorization of contemporary windows is facilitated, as no electricity needs to be interfaced to the moving part.

- Vacuum glass windows are capable of providing a very good performance in terms of thermal insulation at very slim (and thus lightweight) system thickness.

Needless to say, the prototypes presented are not yet available on the market and should be understood as "showcase" suggestions. Future R&D efforts shall address the development of specific parts (motorization and fittings) given that the elements used in FIVA were individually crafted. To become feasible, the motorization shall employ standard components and products. Moreover, the impact of vacuum glass and vacuum glass windows both on normative guidelines on windows and modeling in other (whole building) simulation tools has yet to be worked upon.

Acknowledgement

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