Final Report

Integrated Solution – Double Skin Facade and Diffuse Ceiling Ventilation for School Renovation (I-DIFFER)

Larsen, Olena Kalyanova; Zhang, Chen; Thomsen Nielsen, Lars; Madsen, Mike Vinge; Brøchner Bække, Sara; Tranholm, Gitte Thorup ; Thomsen, Ulrik; Kappel, Niels ; Atzen, Bent

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Larsen, O. K., Zhang, C., Thomsen Nielsen, L., Madsen, M. V., Brøchner Bække, S., Tranholm, G. T., Thomsen, U., Kappel, N., & Atzen, B. (2024). Final Report: Integrated Solution – Double Skin Facade and Diffuse Ceiling Ventilation for School Renovation (I-DIFFER). Department of the Built Environment, Aalborg University. DCE Technical Reports Vol. 2024 No. 321

DEPARTMENT OF THE BUILT ENVIRONMENT
AALBORG UNIVERSITY

Final Report: Integrated Solution – Double Skin Facade and Diffuse Ceiling Ventilation for School Renovation (I-DIFFER)

Olena Kalyanova Larsen
Chen Zhang
Lars Thomsen Nielsen
Mike Vinge Madsen
Sara Brøchner Bække
Gitte Thorup Tranhom
Ulrik Thomsen
Niels Kappel
Bent Atzen

ISSN 1901-726X
DCE Technical Report No. 321

Aalborg University
Department of the Built Environment

BUILD Technical Report No. 321

Final Report: Integrated Solution – Double Skin Facade and Diffuse Ceil-ing Ventilation for School Renovation (I-DIFFER)

by

Olena Kalyanova Larsen
Chen Zhang
Lars Thomsen Nielsen
Mike Vinge Madsen
Sara Brøchner Bække
Gitte Thorup Tranholm
Ulrik Thomsen
Niels Kappel
Bent Atzen

December 2023

Scientific Publications at the Department of Civil Engineering

Technical Reports are published for timely dissemination of research results and scientific work carried out at the Department of Civil Engineering (DCE) at Aalborg University. This medium allows publication of more detailed explanations and results than typically allowed in scientific journals.

Technical Memoranda are produced to enable the preliminary dissemination of scientific work by the personnel of the DCE where such release is deemed to be appropriate. Documents of this kind may be incomplete or temporary versions of papers—or part of continuing work. This should be kept in mind when references are given to publications of this kind.

Contract Reports are produced to report scientific work carried out under contract. Publications of this kind contain confidential matter and are reserved for the sponsors and the DCE. Therefore, Contract Reports are generally not available for public circulation.

Lecture Notes contain material produced by the lecturers at the DCE for educational purposes. This may be scientific notes, lecture books, example problems or manuals for laboratory work, or computer programs developed at the DCE.

Theses are monograms or collections of papers published to report the scientific work carried out at the DCE to obtain a degree as either PhD or Doctor of Technology. The thesis is publicly available after the defence of the degree. Since 2015, Aalborg University Press has published all Ph.D. dissertations in faculty series under the respective faculty. The AAU Ph.D.-portal will host the E-books, where you also find references to all PhDs dissertations published from Aalborg University.

Latest News is published to enable rapid communication of information about scientific work carried out at the DCE. This includes the status of research projects, developments in the laboratories, information about collaborative work and recent research results.

Published 2024 by
Aalborg University
Department of the Build Environment
Thomas Manns Vej 23
DK-9220 Aalborg E, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No 321

Final report

1. Project details

Project title	Integrated Solution - Double Skin Facade and Diffuse Ceiling Ventilation for School Renovation (I-DIFFER)
File no.	64 020-2140
Name of the funding scheme	Energy Technology Development and Demonstration Program (EUDP)
Project managing company / institution	Build, Aalborg University
CVR number (central business register)	29102384
Project partners	Aalborg University, EKOLAB, Windowmaster International A/S, Troldtekt, Aarhus Kommune
Submission date	31 January 2024

2. Summary

English version

The I-DIFFER project aimed to develop and demonstrate a novel, and easily implementable renovation solution that can enhance overall indoor environmental quality in buildings, specifically addressing improvements in air quality, thermal comfort, and acoustics. The project introduces the I-DIFFER solution, which integrates technologies such as the Double Skin Facade (DSF), Diffuse Ceiling Ventilation (DCV), and a ventilation control system. This solution employs a mechanical exhaust system, transporting fresh air through the DSF into the diffuse ceiling plenum and then into the occupied space to ensure satisfactory indoor conditions.

The I-DIFFER project evolved through simulation testing, establishing the fundamental concept of integrating the above-mentioned technologies. The energy performance and comfort were assessed across several scenarios, including variations in the outer layer of DSF, building orientation, etc. Subsequently, the I-DIFFER solution prototype was selected, and evaluated experimentally in a full-scale outdoor façade laboratory. This step was to verify the efficiency of the developed solution in ensuring a high environmental quality and avoiding the potential risk (draught and overheating). An optimized I-DIFFER solution was then implemented at Ellehøjskolen classroom for demonstration. Performance assessment in the demonstration building revealed positive outcomes, including superior air quality, good thermal comfort and strong indications of energy efficiency of the solution.

The I-DIFFER solution developed in this project aligns with market demands for sustainable and non-intrusive renovation options, especially in spaces with high internal loads. The project succeeded in showcasing the solution's effectiveness and validating its reliability. The solution is documented through reporting on the project results in open-source journals. Additionally, a user-friendly design guide has been formulated to facilitate the potential application of the I-DIFFER approach in various buildings, outside of the project consortia.

Danish version

I-DIFFER-projektet havde til formål at udvikle og demonstrere en ny og let implementerbar renoveringsløsning, der kan forbedre det generelle indeklima i bygninger med fokus på luftkvalitet, termisk komfort og akustik. Projektet introducerer I-DIFFER-løsningen, der integrerer teknologier som dobbeltfacade (DSF), diffusloft og et ventilationsstyringssystem. Denne løsning anvender mekanisk udsugning, der transporterer frisk luft udefra gennem DSF, ind til diffusloft og derefter ind i opholdszone.

Udviklingen af I-DIFFER-løsningen involverede en række simuleringer for at etablere grundkonceptet for integration af de nævnte teknologier. Energibehov og komfort blev vurderet i flere opstillede scenarier, herunder egenskaber af facader, og bygningsorientering blev varieret. Herefter blev I-DIFFER-prototypen valgt og testet eksperimentelt i et udendørs facade laboratorie i fuld skala. Dette skridt var for at verificere effektiviteten af den udviklede løsning med hensyn til indeklima og for at minimere potentielle risici som træk og overophedning. En optimeret I-DIFFER-løsning blev derefter implementeret i Ellehøjskolen klasseværelse som demonstration. Resultatvurdering i demonstrationsbygningen afslørede positive resultater, herunder fremragende luftkvalitet, god termisk komfort og viste stærke indikationer på løsningens energieffektivitet.

I-DIFFER-løsningen udviklet i dette projekt stemmer overens med markedets behov for bæredygtige og anderledes renoveringsmuligheder, især til rum med høje interne belastninger. Projektet lykkedes med at vise løsningens effektivitet og bekræfte dens pålidelighed. Løsningen er dokumenteret gennem rapportering af projektresultaterne i internationale tidsskrifter. Derudover er der udarbejdet en brugervenlig designguide for at lette potentiel anvendelse af I-DIFFER-tilgangen i forskellige bygninger uden for projektets konsortier.

3. Project objectives

The primary objective of the project was to develop and demonstrate a comprehensive, but easy to implement, renovation solution that can yield substantial enhancements in overall indoor environmental quality, encompassing air quality, thermal comfort, acoustic comfort. By strengthening passive strategies such as preheating outdoor air in the DSF, mitigating heat losses through the external façade, enabling draft-free ventilation, implementing burglary-safe night cooling, and exploring the control of the solar gains the solution was set not only to optimize the comfort, but also offer comparable to the traditional renovation solutions energy savings or even go beyond those. All in all, the overall objective of the project was therefore in developing a serious alternative to today’s traditional renovation concepts, which is less intrusive and easily implementable.

To achieve the stated objectives, the I-DIFFER project aimed to finalize a comprehensive renovation concept that integrates various technologies, including the double skin façade (DSF), diffuse ceiling ventilation (DCV), and a ventilation and control system. The aim of the project was to merge these technologies into an operational renovation solution while developing supporting documentation for the widespread application of the I-DIFFER solution.

Another key objective was the practical implementation of the I-DIFFER solution in a demonstration case, with the intent to demonstrate its potential and relevance in the building renovation market. Specifically, the project aimed to disseminate its findings through open-source journals and create an easy-to-follow design guide. This guide is intended to support the implementation of the I-DIFFER solution among practitioners.

4. Project implementation

The overall project implementation has proven to be successful, albeit not without challenges. The initial project structure, as defined in the project application, demonstrated efficiency. Activities, milestones, and deliverables were scheduled appropriately, contributing positively to the project's development. However, a delay took place in the final phase of implementation and demonstration, thus compressing many activities in the project's concluding year.

Administrative challenges, including the replacement of a consortium member, coupled with a financial and a technical challenge, were encountered. The financial challenge arose from an economic consideration, leading to the revision of the initial prototype for the I-DIFFER solution, being too costly for real-life implementation. The alternative prototype development, while effective, introduced time-consuming tasks due to the fundamental changes in the I-DIFFER concept.

The technical challenge arose from safety considerations in the general concept design of I-DIFFER, specifically concerning the assurance of access to escape routes through the existing building envelope. This required adapting the I-DIFFER concept to accommodate varying fire-escape solutions in different schools.

All these challenges were successfully resolved, although they did result in a reduction of the monitoring period for the demonstration building. The monitoring results in the demonstration building were therefore supported by monitoring in AAU laboratory to expand the evaluation period of I-DIFFER solution. The obtained results confirm the general success of the developed renovation solution. However, certain weaknesses in the solution have been identified and are addressed in the subsequent sections of this report.

During the course of the project, the project consortium applied for and received approval from EUDP for project modifications, including changes to the timeline, replacement of a consortia member, and adjustments to the budget.

5. Project results

General

The primary objective of the I-DIFFER project was to formulate and demonstrate an integrated solution tailored for building renovations, positioned as a viable alternative to conventional renovation approaches. Specifically designed for application in buildings with significant internal loads and, consequently, high ventilation demands, the solution addresses the challenges related to renovation of building envelope, upscaling existing ventilation systems or installing new balanced mechanical ventilation in buildings. In such scenarios, the I-DIFFER solution is sought as another appealing option.

This objective was successfully accomplished by identifying specific I-DIFFER elements requiring in-depth characterization and performance evaluation, as elaborated in the following paragraphs and in several publications (Bugenings *et al.*, 2022; Schaffer *et al.*, 2023). As a result, information about factors like the importance of orientation of the building's exterior, properties of the building envelope, role of internal loads and schedules, and more were established for optimisation of I-DIFFER architecture.

The focus extended to the development of the control system of the I-DIFFER solution, encompassing both the software and hardware interface for optimal operation. Subsequently, the developed solution was tested in a full-scale outdoor test facility at Aalborg University (Chen Zhang *et al.*, 2023) and then implemented for a classroom in the demonstration building, Ellehøjskolen (Figure 1, Figure 2, Figure 3, Figure 4). As a concluding step, a Design Guide has been formulated, providing guidelines to practitioners for tailoring the I-DIFFER solution to other buildings (Larsen *et al.*, 2023).

Figure 1. Façade of Ellehøjsskolen prior renovation.

Figure 2. Façade. Left – prior renovation. Right – after renovation with I-DIFFER.

I-DIFFER Concept

Externally, an additional transparent (semi-transparent) layer is introduced to the pre-existing building envelope, forming as a Double-Skin Façade (DSF). Internally, a diffuse ceiling (DC) is added for ventilation air supply, Figure 5. An installed mechanical exhaust in the room and intelligent control of airflow direction, ensures good air quality and energy efficiency. Operational strategy is then realized through the control of openings in the DSF, Figure 6.

In warmer seasons, the DSF system can aid the reduction and removal of the solar heat gains in the occupied space. The reduction is due to solar radiation being captured in DSF before entering the room and then removed from DSF by natural ventilation. The heat removal is ensured by allowing air to bypass the facade and enter the diffuse ceiling directly from the outside, Figure 6. In cooler seasons, the air passes the DSF and preheated before entering the DC plenum.

Figure 3. Interior view: ceiling before.

Figure 4. Interior view: ceiling after.

DC ventilation utilizes suspended ceiling panels to deliver fresh air directly into occupied space. It effectively reduces draught risk by supplying low-momentum air, while minimizing the need for extensive ductwork and permitting the use of acoustic panels as air diffusers. In the hot season, DC ventilation through the bypass can facilitate the thermal mass activation, particularly when used for night cooling.

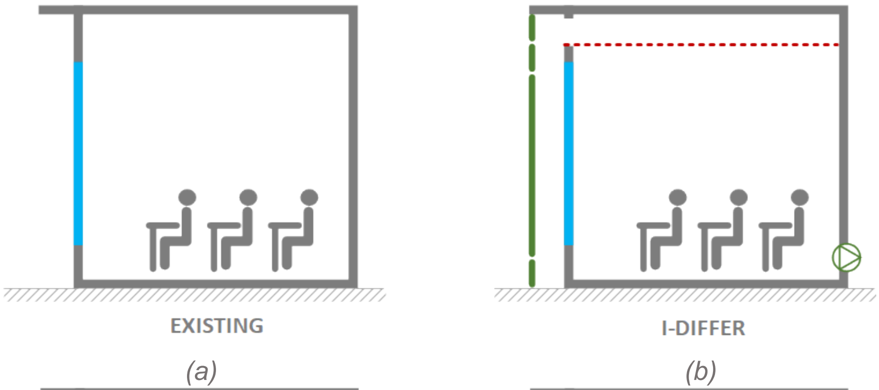

Figure 5.
(a) Pre-existing building.
(b) I-DIFFER: DSF, DC and exhaust fan introduced to an existing building.

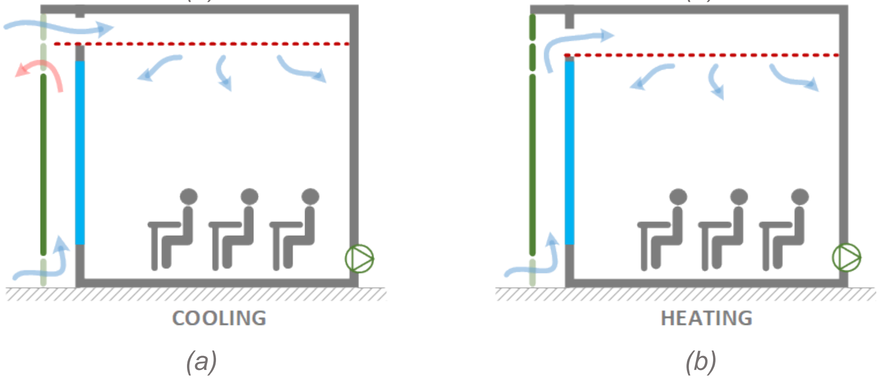

Figure 6. Key operational strategies of I-DIFFER.
(a) Cooling strategy
(b) Heating strategy

The control system maintains optimal indoor conditions in the occupied space by adjusting the ventilation rate and managing the direction of heat gains and losses. This is achieved by coupling/decoupling the DC plenum and the double-skin façade. Additionally, the shading system in the DSF cavity can be integrated into the I-DIFFER control.

Performance assessment – simulation testing

Another important project objective was to develop a solution that can offer good indoor environmental quality, specifically addressing improvements in air quality, thermal comfort, acoustic conditions and visual comfort (efficient shading). Simultaneously, the developed solution sought to meet or exceed the energy efficiency standards set by traditional renovation approaches. To address this dual objective, a thorough evaluation of energy consumption and Indoor Environmental Quality (IEQ) within a representative building was carried out by modelling, using IDA-ICE. Systematic testing explored the impact of variables like façade orientation, thermophysical characteristics of the existing façade, properties of the second skin (exterior layer of double façade), optical features of glazing and shading, and thickness of the double-skin façade cavity, alongside various occupancy loads. These assessments identified both optimal and suboptimal performance scenarios, accounting for future climate change and potential heat waves (Bugenings *et al.*, 2022; Schaffer *et al.*, 2023). The overall findings from this work document the efficiency of I-DIFFER solution, both in terms of energy performance and comfort.

Performance assessment - experimental testing

Documenting the performance of I-DIFFER by monitoring, was also among the project's objectives. The first prototype of the I-DIFFER solution was installed and tested in the AAU full-scale facility. The initial performance of the I-DIFFER solution was compared in parallel to a traditional renovation solution installed in an identical room. This comparison was carried out without any control system implemented, thus addressing only the behaviour of the room as a result of I-DIFFER operated either in permanently cooling or heating mode. (Figure 6). The results of this assessment, published in (Chen Zhang *et al.*, 2023) reveal that the I-DIFFER solution achieved thermal comfort comparable to or even superior to traditional renovation solutions. During winter, the

Double-Skin Facade effectively recovered transmission losses through the existing facade and captured heat gained from solar radiation. In summer, air ventilated the DSF cavity, acting as an air curtain to mitigate solar gains. As a result, it decreased heat gain in the room, maintaining a lower indoor temperature than the traditional solution. Through the added benefit of activating thermal mass, I-DIFFER can reduce peak operative temperature and shift the peak hour to later in the day.

Figure 7. The photo illustrates the façades of two rooms at the AAU laboratory. The room on the left features the I-DIFFER solution, while the room on the right represents traditionally renovated façade.

Figure 8. The photo depicts the interior of two test rooms at the AAU laboratory. The room on the left features the I-DIFFER solution, while the room on the right represents traditionally renovated façade

Similarly to the prototype of I-DIFFER architecture (Figure 7), a prototype of control system was developed for the project and then tested at AAU laboratory. The overall findings from testing suggest that the I-DIFFER system effectively maintains a draught-free environment and demonstrates competitive thermal comfort conditions.

An example of the monitoring results in the AAU laboratory, featuring the implemented control system, is illustrated in Figure 9. The figure features monitoring results for a test room facing towards South with the internal load of 50 W/m^2, which corresponds to a standard classroom. All measurements performed without shading device during the heatwave in summer 2023. The results reveal that the peak temperature occurs first in the afternoon, as intended for the system performance. The maximum operative temperature exceeds the guidelines, but only within the shorter periods. The results document good performance of the system, considering the absence of solar shading and the heatwave conditions.

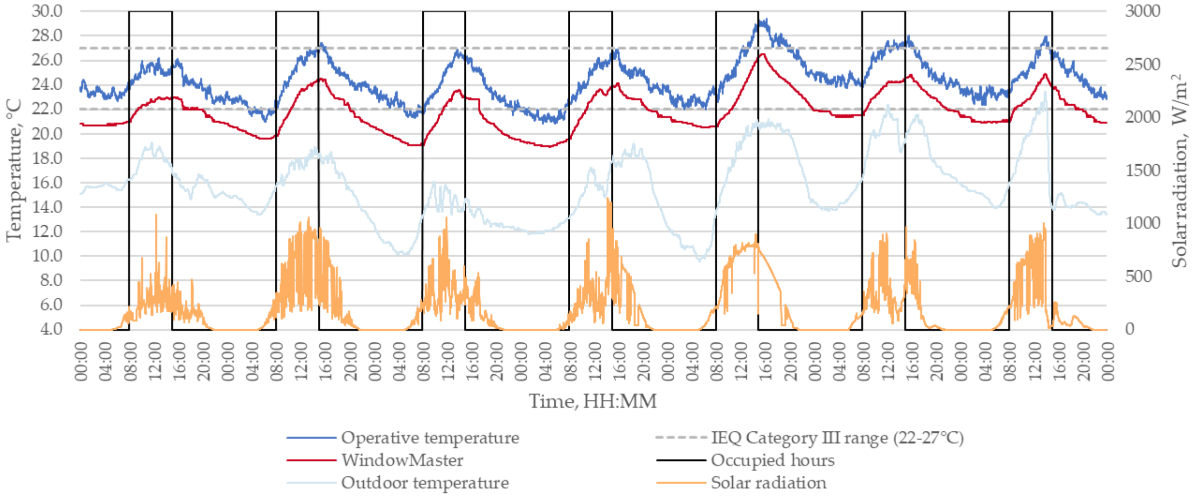

Figure 9. Example of monitoring results in AAU test room with implementation of control system during the heatwave in Denmark.

One of the primary potential risks identified for the I-DIFFER solution is the occurrence of draught. Thus thermal comfort, both local and global, was evaluated in 9 locations in the test room for the implemented I-DIFFER solution in the AAU laboratory. The assessment spanned one week in August 2023, four days in November 2023, and four days in December 2023, all conducted with the implemented control strategy. The results of this evaluation are anticipated to be published in the coming year, documenting overall good performance.

In Figure 10, the highest monitored draught rates for three different locations in the room can be seen. These were observed in November monitoring campaign. Throughout the whole period, the draught rate consistently remained below 11%, while the acceptable rate for *IEQ category II* is within 20%. Consequently, it is concluded that the I-DIFFER solution does not pose a risk of draught.

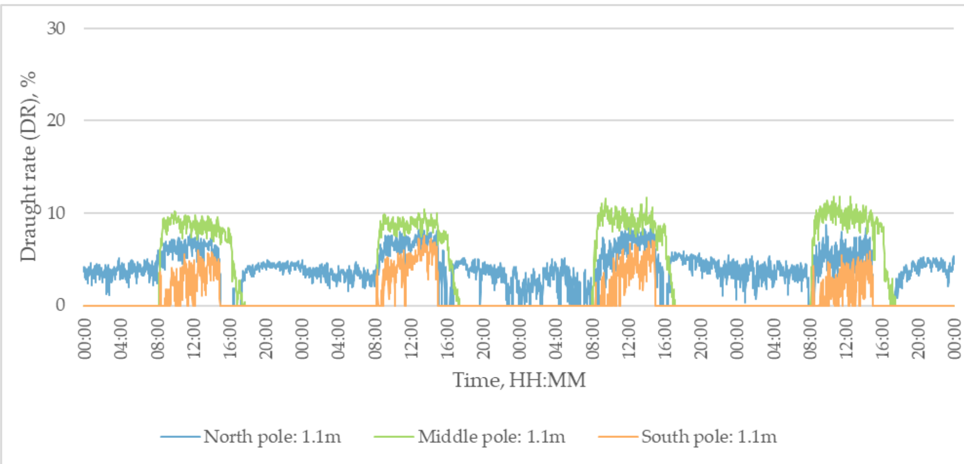

Figure 10. Draught rate calculated based on measurements in AAU laboratory in November 2023. The data is reported for 3 different locations.

Technology developed and implemented

The I-DIFFER solution underwent testing in a full-scale laboratory setup at Aalborg University. Afterwards it was modified to reduce the associated costs and to integrate the fire-escape openings possibilities. Final solution was subsequently implemented at Ellehøjskolen for demonstration purposes. The overall description of the demonstration case can be found in WP5 report (Zhang *et al.*, 2024), and the Design Guide (Larsen *et al.*, 2023) provides recommendations for practitioners for adapting the I-DIFFER solution for implementation in other buildings.

Double-Skin Façade. The second skin (outer layer of DSF) covers only the fixed, unopenable windows in the existing façade to retain the fire escape openings (Figure 11). This design choice resulted in small niches in each section, accommodating not only fire escape windows, but also doors, as commonly found in schools. Additionally, it created discreet access for maintenance personnel to the DSF from outside, facilitating tasks such as filter replacement, cleaning, and other maintenance requirements.

Figure 11. Preserved fire escape opening (inside and outside view). Access to DSF for maintenance.

Diffuse ceiling. The distribution of active (shaded) and passive panels in the classroom, including lighting fixtures (circles) are shown in Figure 12. Notably, due to system modulation, the plenum is divided into two sections (left and right). The design considerations of the diffuse ceiling in Ellehøjskolen were supported by CFD modelling to evaluate the consequences of the plenum height and the location of the opening between plenum and DSF. The distribution of active panels in these two sections is intentionally different and therefore allows to assess user preferences to one or the other solution in the future.

Interface between DSF and DC plenum. An interface, between DSF and DC, to integrate a ventilation filter and the fan was developed Figure 13. This interface also serves a purpose of supplying air to the DC plenum both directly from the outside or from the DSF. It is comprised of a box housing a fan and filter. The box is attached to the existing facade, and connected to the DC plenum through an existing opening. More information about the interface can be found in the Design Guide (Larsen *et al.*, 2023).

Control system.

The indoor climate control system installed is WindowMasters NV Embedded®. A flexible solution that can be established via BACnet, KNX, or Modbus. Four control zones are defined for the system (Figure 14, Figure 16). Similarly to DC plenum, the DSF is also divided into 2 parts, resulting in two control zones: (1) Classroom, (2) DSF Left, (3) DSF Right, (4) Diffuse ceiling plenum. Detailed description of the control can be found in WP3 report (Tranholm and Thomsen, 2023). The system employs separate operational strategies for summer and winter, automatically transitioning between them based on the outdoor temperature and the heating/cooling requirements in the room. Different operational modes are available for each strategy.

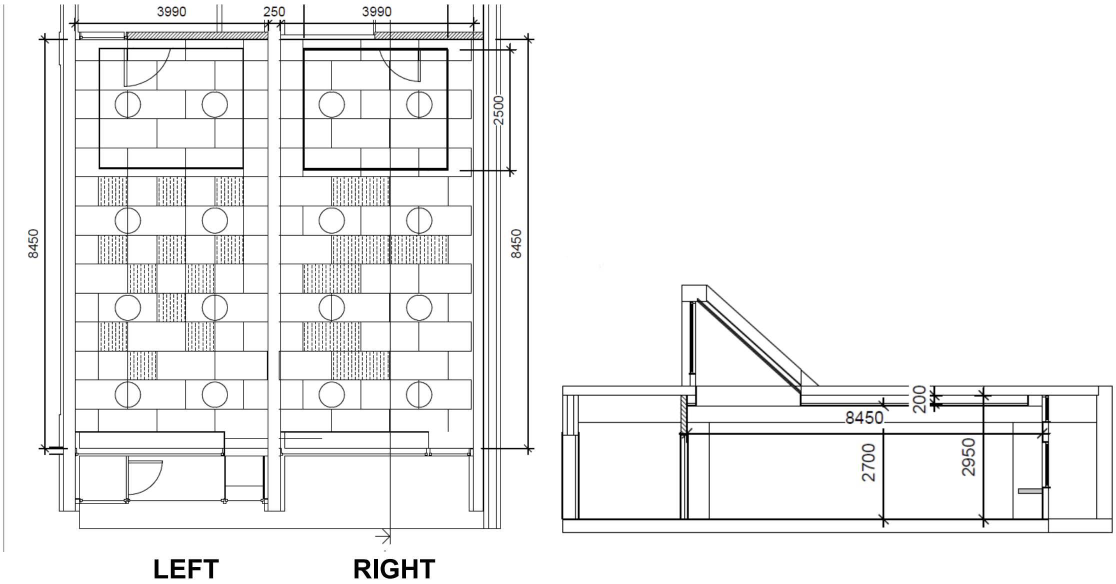

Figure 12. Plan and section of diffuse ceiling construction.


Figure 13. Interface between DSF and DC plenum in Ellehøjskolen.

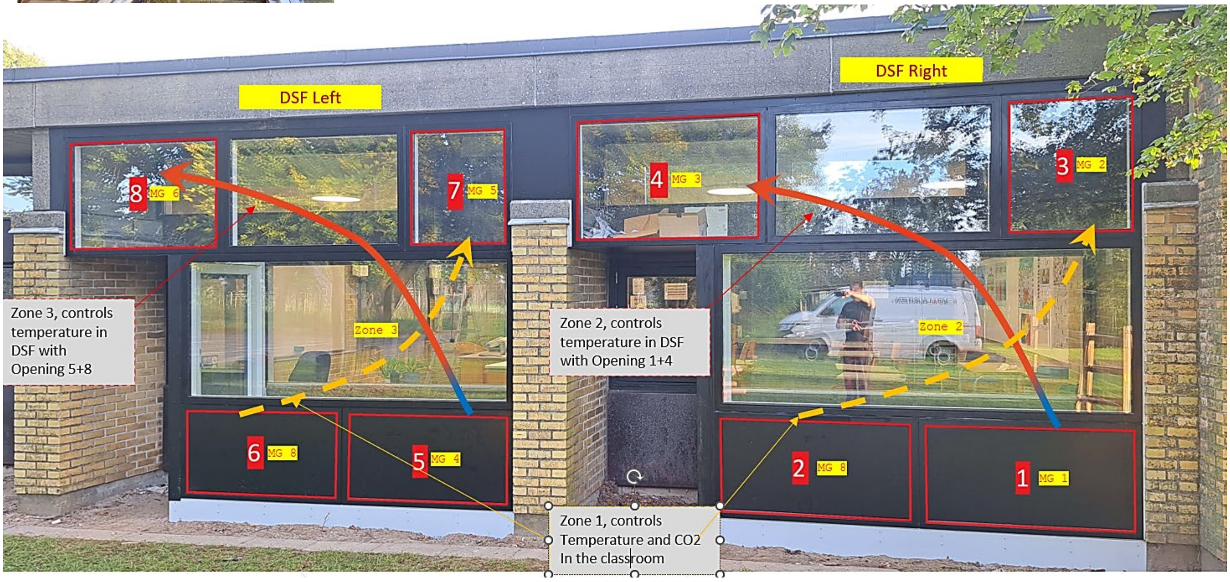

Figure 14. Zones and controlled openings in Ellehøjskolen.

Figure 15. Controllable openings of the exterior façade.

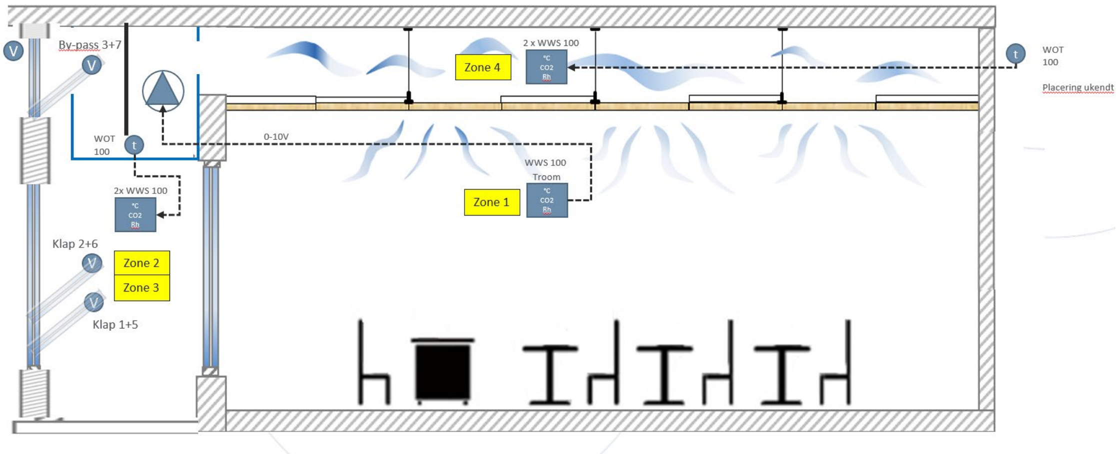

Figure 16. Zone distribution and associated control links.

The Table 1 illustrates the types of operational modes the system features and indicates in which strategy they are accessible. In each section of the façade (Left and Right) there are four openings that can be operated and controlled, these are shown in the Figure 14, specified in Figure 15 and described as following:

Inlet Openings: These openings (opening 1,2,5,6) allow air to enter the DSF. Openings are evenly distributed horisontally for optimal preheating. Ideally, they should be top-hang openings.

Outlet Opening: This opening in each secrion (opening 4 and 8) is designed to discharge warm air from the DSF. Ideally, it should extend across the entire width of the facade to ensure even cooling down of the DSF.

Bypass Opening: This opening in each section (opening 3 and 7) controls the ventilation strategy of the system, for more information please read about the by-pass opening above.

Table 1. Operational modes for Summer and Winter control strategies.

Operational Mode	Description	Summer	Winter
Night Cooling	Efficient for cooling. Used when the building is unoccupied at night. The maximum opening degree of the windows can be limited via system parameters if necessary.	Yes	No
Pulse Ventilation	Short window opening with immediate closure to create minimum air exchange in the building. The pulse duration and opening size can be adjusted based on room temperature, CO2 levels, and weather conditions.	Yes	Yes
Temperature Controlled Natural Ventilation	The windows are opened or closed, based on outdoor and room temperaturesand CO2.	Yes	No
Gap Ventilation	Windows are slightly opened (small opening degree). Their opening/closing is defined by room temperature, CO2 levels inside/outside, and weather conditions, ensuring continuous air exchange.	Yes	Yes
Manual Operation	Windows are opened/closed via control pressure/app and then return to automatic operation after a specified time, typically 30 minutes (this period can be changed, e.g., to 15 minutes).	yes	Yes

Performance assessment – demonstration case

Several datasets were collected for the performance evaluation of the implemented I-DIFFER solution in Ellehøjskolen. These datasets include information from WindowMaster sensors stored in the cloud, as well as data from additional sensors installed by project partners to ensure sufficient data availability.

The WindowMaster sensor data is available only for the post-renovated classroom, starting from September 26th, 2023. This dataset provides details on CO2 concentration and temperature measured in all associated zones, control strategy in use, and outdoor air temperature. Additional sensors were set up in both the class-room selected for renovation and a reference classroom to compare the I-DIFFER performance against an unrenovated room. These sensors were configured to measure:

- Indoor temperature and CO2 levels in the renovated classroom and reference classrooms, starting from April 2023.
- Energy consumption per radiator in both the renovated and reference rooms, starting from April 2023.

Air quality

Due to both rooms functioning as flex-rooms in Spring 2023, making them unrepresentative of typical class-room conditions, a comprehensive comparison of energy use, CO2 levels, and temperature before and after renovation is not feasible. However, with the start of the new school year in August 2023, normal use and operation of the demonstration classroom resumed. Data for the classroom under the normal operation before renovation was collected from August 14th, revealing instances of CO2 concentration reaching up to 3000 ppm (Figure 17). The full implementation of the I-DIFFER solution from September 26th resulted in a significant improvement in indoor air quality, as shown in Figure 17 and Figure 18, with the maximum CO2 concentration staying below 1250 ppm in the operation hours.

Thermal comfort

Concerning changes in thermal comfort before and after renovation, the results at the present moment are inconclusive. Periods of low temperature occur in the renovated room (Figure 17 and Figure 19), but these are linked to unknown radiator settings and user behavior during the monitoring period. An inspection of the class-room was conducted in January 2024, during which the radiator settings were controlled to ensure that the heating system can effectively respond to the thermal needs of the room, indicating that the performance of I-DIFFER solution in the future can benefit from integrating the heating system with the ventilation system. Consistent with this finding, occupants in the classroom have reported feeling that the thermal environment is slightly cool, while overall evaluation of the renovated solution is positive (Figure 22).

In terms of local discomfort such as draught, radiant asymmetry and more, the I-DIFFER solution was tested for various conditions in AAU laboratory, where the risk of draught was eliminated (Figure 10). Nevertheless, it could be beneficial to investigate this potential issue in the demonstration building in the future.

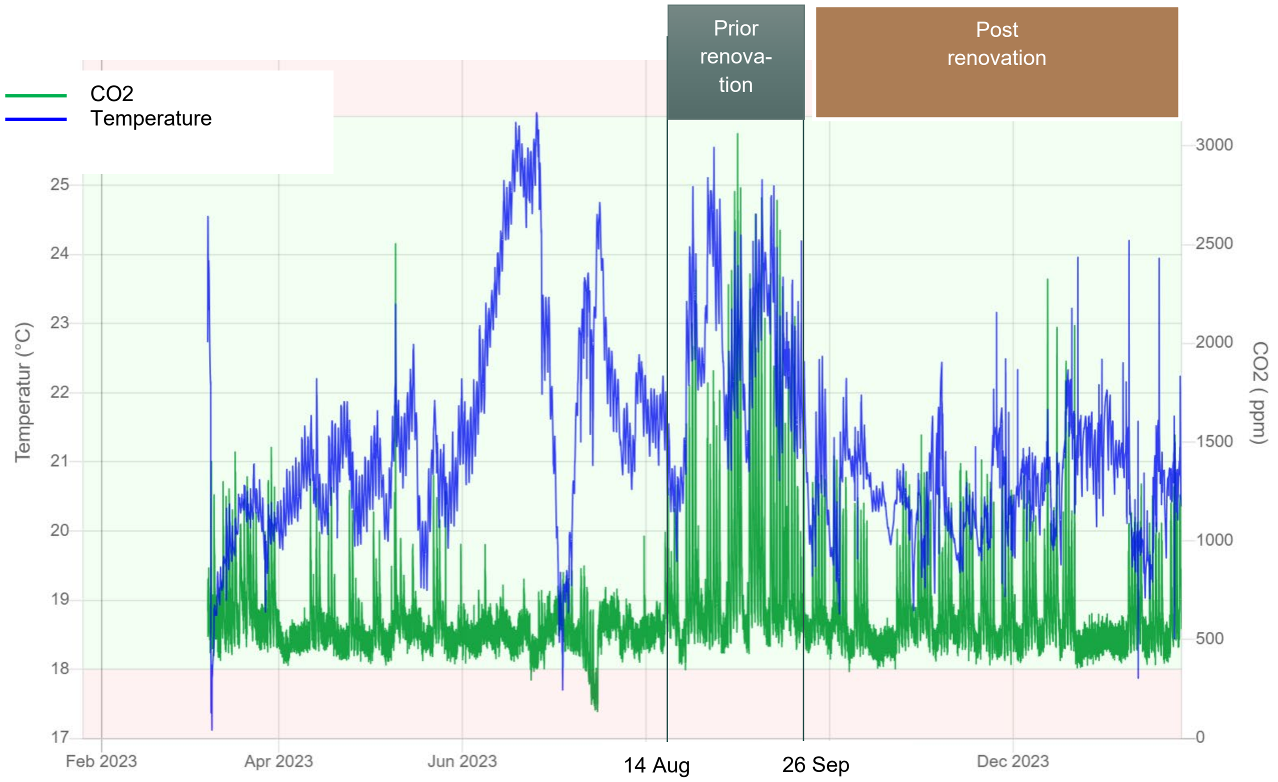

Figure 17. Indoor temperature and CO2 in the classroom. Marked period identifies normal use prior to renovation.

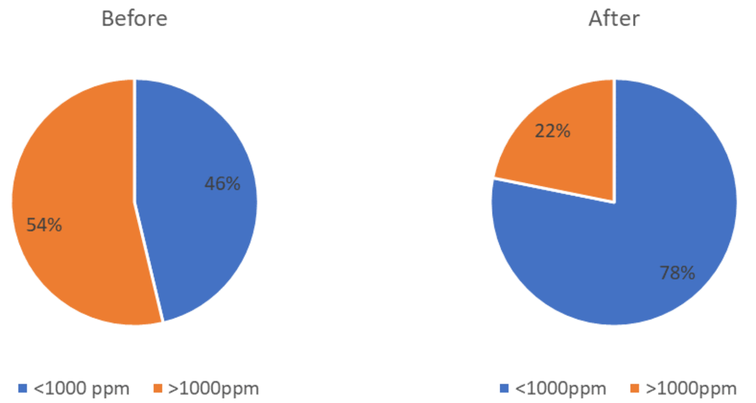

Figure 18. CO2 in the classroom during occupied hours before and after implementation of I-DIFFER solution.

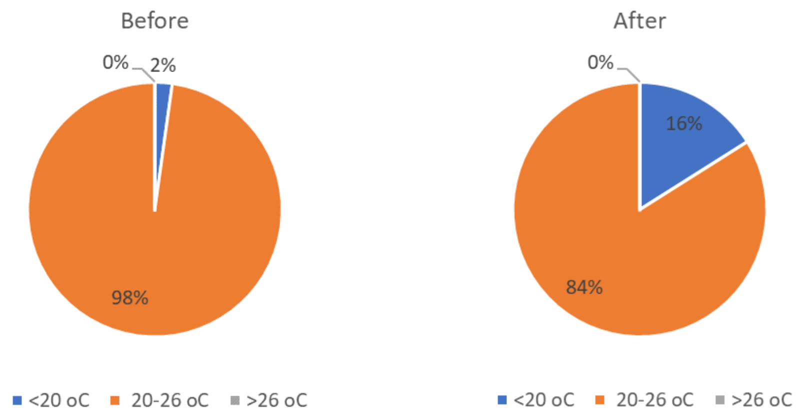

Figure 19. Indoor temperature in the classroom during occupied hours before and after implementation of I-DIFFER solution

Acoustic comfort

A reverberation time has been measured in the classroom before and after the implementation of the I-DIFFER solution. Measurements are carried out in accordance with SBI-anvisning 217 (2017) and the results are related to BR18 corresponding to the requirement specifications in SBI-anvisning 218 (2008). The required values comply with in all frequency bands.

As shown in Table 2, the reverberation time before renovation was in the range of 0.8-1 s, which did not meet the BR18 requirements in the classroom. After establishment of the new ceilings, the reverberation time has been reduced significantly and the requirements have been met in all frequency bands. It is noticeable that the new Troldtekt ceiling resulted in a significant and much clearly audible difference, to the great benefit of the indoor acoustic comfort.

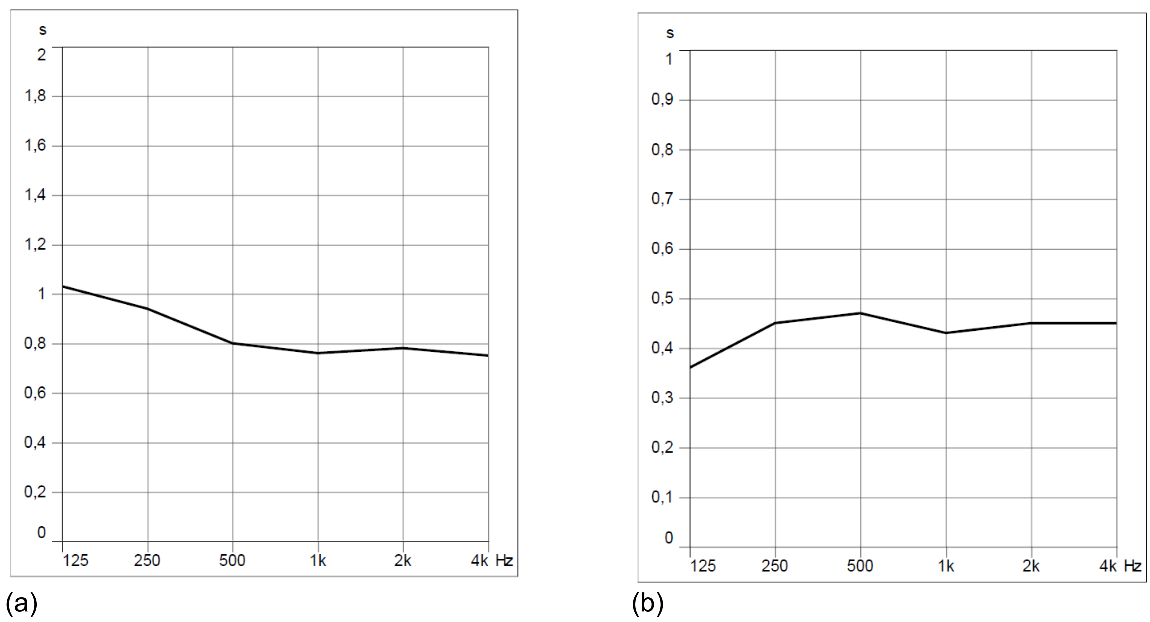

Figure 20. Reverberation time in all frequency bands (a) before renovation (b) after renovation

Table 2. Reverberation time before and after renovation

Efterklangstid T i sek.	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	Krav overholdt
Før etablering	1,0	0,9	0,8	0,8	0,8	0,8	Nej
Efter Troldtekt	0,4	0,5	0,5	0,4	0,5	0,5	Ja
Krav (T60 max)	0,7	0,6	0,6	0,6	0,6	0,6	

Visual performance

The visual performance of the I-DIFFER solution poses a challenge, mainly because the integration of the second façade layer leads to a reduction in daylight availability. It becomes crucial to ensure a satisfactory amount of daylight from alternative sources. In the demonstration building, skylights are employed to guarantee sufficient daylight availability. Simultaneously, the I-DIFFER solution has the potential to enhance visual comfort by minimizing glare, particularly if a solar shading system is integrated. However, in the case of the demonstration building, the incorporation of solar shading was deemed unnecessary owing to the presence of large overhangs and surrounding trees.

Energy performance

The energy performance of the I-DIFFER solution was evaluated by comparing the heating consumption in both the test classroom and a reference classroom before and after the implementation of the I-DIFFER solution. The energy meters were installed in both rooms to measure the heating consumption of radiators. In each room, there are two radiators, and consequently, four energy meters were installed. These meters enable a rough estimation of the I-DIFFER effect, although uncertainties will be present due to variations in occupant presence, behavior and potentially different heating setpoints.

Saving potential of I-DIFFER solution can be seen from Figure 21. The renovated classroom has higher heating consumption than the reference room before the renovation, while it is lower after the implementation of the I-DIFFER solution. It is worth to mention that the control of heating system was not included in the current control strategy of I-DIFFER solution. Therefore, the heating system could not operate optimally to explore the full potential of the renovation solution. As a consequence, a lower indoor temperature was observed in the renovated classroom. On one hand this observation indicates that the saving potential of I-DIFFER might be overestimated, but on the other hand the savings are obvious along with good to superior air quality in the renovated classroom.

Evaluation by occupants

On December 14, 2023, pupils and teachers in the recently renovated classroom received a questionnaire (*Figure 22*) addressing topics such as their perception of the room before and after renovation, including indoor climate conditions (temperature, air quality, ventilation, noise, and lighting). A total of 15 anonymous responses were collected. While there has been considerable variation in the responses, the overall assessment of the renovation solution is rather positive.

- *General Perception of the Room:* Predominantly positive, indicating improvement post-renovation.
- *Temperature and Air Quality:* Neutral responses with a wide range of both positive and negative feedback; on average there is limited improvement noted post-renovation.
- *Ventilation and Noise:* Neutral responses with a diverse range of positive and negative feedback; on average there is limited improvement post-renovation.
- *Lighting:* Very positive feedback with a significant improvement.

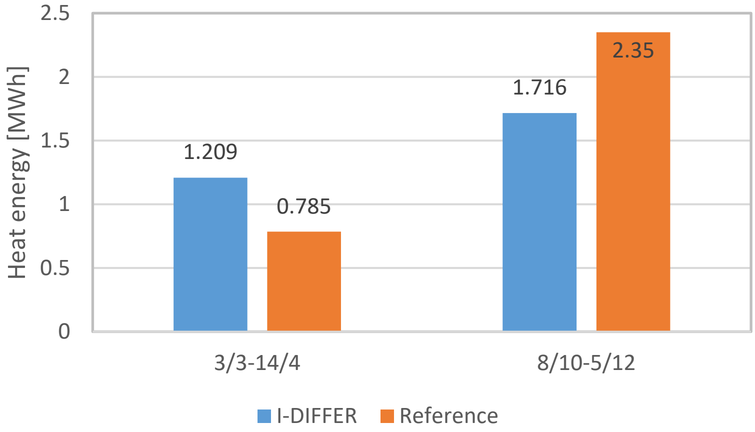

Figure 21. Heating consumptions in the test classroom and reference classroom.

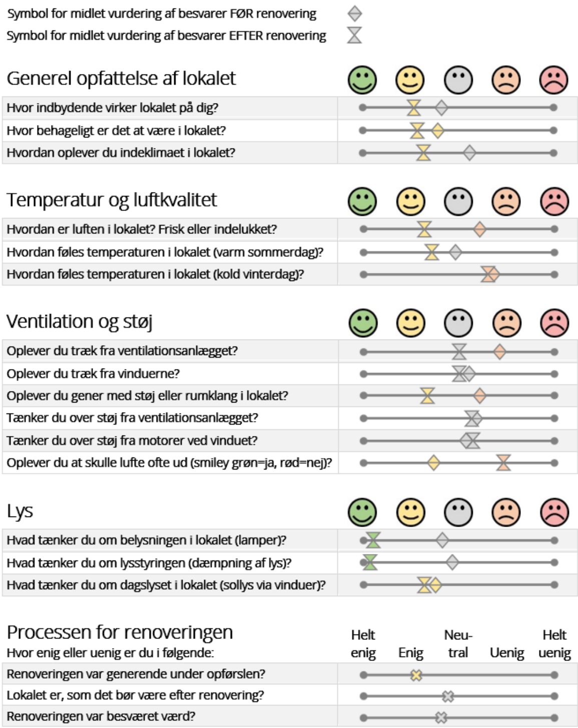

Figure 22. An example of questionnaire layout distributed among the occupants.

Specific answers from the occupants, similar to the monitoring data for the renovated classroom, which indicates that the operative temperature in the room tends to be in the lower end of the comfort range. This was particularly relevant during the extreme cold outdoor conditions in January 2024, highlighting the importance of coupling ventilation and heating control strategies in the future application of the I-DIFFER solution.

In summary, the performance evaluation of the I-DIFFER solution in the demonstration building closely aligns with the anticipated outcomes outlined for this project. The I-DIFFER solution have met the initial project expectations and its the core features have been successfully validated within the project. Including ease of installation, assurance of optimal indoor air quality, and the potential for energy consumption reduction. However, the assessment of thermal comfort has yielded varied results, prompting considerations for potential improvements. Integration of heating system control with the ventilation system is recognized as crucial for optimizing performance. Looking ahead, a supplementary study to monitor the risk of draught in the demonstration building can aid the assessment of additional refinements for heating strategy in I-DIFFER buildings.

The Technology and the Market

Tailored for the Nordic and European markets, especially spaces with high internal loads, the I-DIFFER solution not only aligns well with current sustainability goals in the building sector and society but also offers a swift and non-intrusive installation, making it a valuable solution for diverse building renovation projects. The project relies on the growing interest in a healthy indoor environment, particularly in educational institutions like schools. With the ongoing refurbishment of Danish schools and returning interest to passive and energy-efficient design solutions, the I-DIFFER solution aligns well with present market demands.

The I-DIFFER project has successfully achieved its goal of developing and showcasing an integrated solution for building renovations that offers a compelling alternative to traditional methods. The combination of Double-Skin Facade (DSF) and Diffuse Ceiling Ventilation (DCV) technologies has demonstrated its effectiveness in enhancing indoor environments, addressing crucial factors such as air quality, thermal comfort, and acoustic performance. The success in demonstrating the performance of I-DIFFER solution, both under laboratory conditions and for the renovation of school classrooms, validates the reliability and validity of the solution, facilitating its market entry. However, the building industry is conventionally slow, and at this moment, it is not yet possible to demonstrate the application of I-DIFFER solution in other cases than Elehøjskolen. The I-DIFFER solution is now included in the portfolio of the project partners, carefully described in scientific and technical journals, and presented at national and international conferences. Furthermore, a design guide is developed to facilitate the future application of the solution within the industry.

However, it is essential to mention that the cost associated with the developed solution although optimized, is still high. Combined with the need for solution customization in each specific case, may pose difficulties for the solution to access the market at the anticipated rate. Further development, as described in section 7 on page 19, might be needed to ensure its strong position in the market.

Regarding the scientific exposure of the solution on the international market, publications describing the solution are well-cited internationally, especially in publications related to improving the energy performance and comfort of schools and daycare institutions. Additionally, the project has garnered significant interest among industry representatives at the CISBAT conference.

Dissemination of knowledge know-how

During the project period, continuous efforts have been made to disseminate project results and know-how, targeting potential customers and stakeholders on both the usage and production sides of the technology. This included architects, consulting engineers, building owners, municipalities, developers, producers, as well as researchers working within the field.

The dissemination activities include:

- IEA Technical Day in Copenhagen (June 2023). At this event the project results were presented providing an exposure of the solution developed within the project to Danish and international audience, both industry and researchers.
- Publication in DANVAK HVAC Journal (Tranholm *et al.*, 2022). The initial I-DIFFER concept was documented and published in the DANVAK HVAC journal, contributing to the dissemination of the project work within the industry in Denmark.
  https://ipaper.ipapercms.dk/TechMedia/HVACMagasinet/2022/2/?page=60
- Presentation at CISBAT 2023, International Scientific Conference in Switzerland. Two papers (Hu *et al.*, 2023; C. Zhang *et al.*, 2023) were presented at the prestigious peer-reviewed CISBAT 2023 conference, further extending the reach of the project results internationally.
- High-Impact International Journals. The results of the project have been disseminated through publication in renowned peer-reviewed international journals (Bugenings *et al.*, 2022; Chen Zhang *et al.*, 2023; Schaffer *et al.*, 2023), including the Journal of Building Engineering and Building and Environment.

Published journal articles entitled as following:

- "A novel solution for school renovations: Combining diffuse ceiling ventilation with double skin façade."
- "Exploring the potential of combining diffuse ceiling and double-skin facade for school renovations."
- "Experimental investigation of an integrated renovation solution combining diffuse ceiling ventilation and double skin façade."

After the project has finished, additional works are anticipated to be published, focusing on the control strategy of the developed solution and presenting the results of the demonstration building monitoring.

List of references

Bugenings, L.A. *et al.* (2022) 'A novel solution for school renovations: Combining diffuse ceiling ventilation with double skin facade', *Journal of Building Engineering*, 49, p. 104026. Available at: https://doi.org/10.1016/J.JOBE.2022.104026.

Hu, Y. *et al.* (2023) 'Energyplus model of double skin façade and diffuse ceiling ventilation', *Journal of Physics: Conference Series*, 2600(6), pp. 1–6. Available at: https://doi.org/10.1088/1742-6596/2600/6/062003.

Larsen, O.K. *et al.* (2023) 'Design Guide for I-DIFFER: The Double-Skin Facade Solution with Integrated Diffuse Ventilation'. Aalborg: Aalborg University, p. 22.

Schaffer, M. *et al.* (2023) 'Exploring the potential of combining diffuse ceiling and double-skin facade for school renovations', *Building and Environment*, 235, p. 110199. Available at: https://doi.org/10.1016/J.BUILDENV.2023.110199.

Tranholm, G.T. *et al.* (2022) 'Helhedsorienteret og skånsom energi- og indeklimarenovering', *DANVAK*, p. 3.

Tranholm, G.T. and Thomsen, U. (2023) 'STYRINGSSTRATEGI FOR I-DIFFER - Dobbeltfacade Integreret med Diffusloft Ventilation til Renovering af Skoler [WP3-WP5 reporting]'. Aalborg: Windowmaster International A/S.

Zhang, Chen *et al.* (2023) 'Experimental investigation of an integrated renovation solution combining diffuse ceiling ventilation and double skin façade', *Building and Environment*, 246, p. 111000. Available at: https://doi.org/10.1016/j.buildenv.2023.111000.

Zhang, C. *et al.* (2023) 'Experimental study of the performance of a novel solution with double skin façade and diffuse ceiling ventilation', *Journal of Physics: Conference Series*, 2600(102007), p. 102007. Available at: https://doi.org/10.1088/1742-6596/2600/10/102007.

Zhang, C. *et al.* (2024) 'I-DIFFER solution: Demonstration in Ellehøjskolen Technical report'. Aalborg: Aalborg University.

6. Utilisation of project results

The results of this project have expanded the market potential of WindowMaster, Troldtekt, and Ekolab nationally and internationally. The developed I-DIFFER solution enables partners to meet diverse demands from clients and architects, unlocking new opportunities in the technology market. It not only fulfils the need for alternative swift renovation solutions to support carbon-neutral building development but also addresses the requirements of buildings with strict IEQ standards, resulting in high ventilation demand.

The project has facilitated knowledge transfer, enhanced market positions, and enriched the expertise of all partners involved. This involves broadening their range of products, gaining new skills and knowledge, expanding collaboration networks, both in scientific and non-scientific domains. Among other accomplishments in this project, Troldtekt has demonstrated an alternative application for their products linking the acoustic panels with the façade renovation and aiding in their market expansion. WindowMaster progressed in development of control strategies linking several thermal zones (double-skin façade, diffuse ceiling plenum and the occupied space), but also integrated the possibility for solar shading control as new feature in their product portfolio. Aalborg University supported WindowMaster by experimental testing of the developed strategies and will continue disseminating the project results. Ekolab, specializing in sustainable school renovations, gained valuable know-how and expanded their project portfolio. Aarhus Municipality successfully carried out the demonstration with minimal interference to users, aligning with their strategic plans for improved indoor climate in school buildings. The municipality has a large pool of buildings awaiting renovation, where the I-DIFFER project results can be applied in a larger scale. Thus in terms of commercial results, the project opens the possibilities for increased turnover, exports, employment, with expectations of further growth.

From a research and development perspective, this project has successfully developed a solution that can be realised using a range of products available in the market. These products include windows, façade elements, air-permeable acoustic panels, controllable openings, dampers, motors, actuators, and more. The project partners, being the front-runners in applying the developed solution, hold the advantage of acquired knowledge and the assurance that their respective products align with the developed solution. Furthermore, the results of this project demonstrate the potential for future product development. Specifically, the developed solution holds the potential to evolve into a modular plug-and-play product that can be accompanied by a configuration tool to support the decision-making for façade modulation in each specific case.

7. Project conclusion and perspective

The I-DIFFER project has successfully accomplished its goal of developing and showcasing an integrated solution for building renovations that offers a compelling alternative to traditional methods. The combination of Double-Skin Facade (DSF) and Diffuse Ceiling Ventilation (DCV) technologies has demonstrated its effectiveness in enhancing indoor environments, addressing crucial factors such as air quality, thermal comfort, and acoustic performance. Rigorous simulations and laboratory testing have validated the system's adaptability to various conditions, showcasing the efficient use of passive strategies for optimized performance.

To enhance market adoption, reducing the need for customization of the developed solution is crucial. This can be achieved through further product development into a modular plug-and-play system, minimizing customization efforts. A development of a configuration tool, to address both hardware customization and performance/control strategy optimization, would support decision-making among consulting engineers. Availability of such a tool will also improve the accessibility of the developed solution in the market. Lastly, a comprehensive assessment of the environmental impact of the developed solution in comparison to other renovation means is needed to ensure market acceptance.

Thus, moving forward, the next steps for the technology shall involve refining and potentially transforming it into a modular plug-and-play product, development of a configuration tool either for the I-DIFFER solution or its modular “brother” followed by an environmental impact assessment of the technology against other competitors on the market.

8. Appendices

Please see the publications that describe and document the performance of I-DIFFER solution by following links provided for each article:

Bugenings, L.A. *et al.* (2022) 'A novel solution for school renovations: Combining diffuse ceiling ventilation with double skin facade', *Journal of Building Engineering*, 49, p. 104026. Available at: https://doi.org/10.1016/J.JOBE.2022.104026.

Schaffer, M. *et al.* (2023) 'Exploring the potential of combining diffuse ceiling and double-skin facade for school renovations', *Building and Environment*, 235, p. 110199. Available at: https://doi.org/10.1016/J.BUILDENV.2023.110199.

Zhang, C. *et al.* (2023) 'Experimental investigation of an integrated renovation solution combining diffuse ceiling ventilation and double skin façade', *Building and Environment*, 246, p. 111000. Available at: https://doi.org/10.1016/j.buildenv.2023.111000.

Tranholm, G.T. *et al.* (2022) 'Helhedsorienteret og skånsom energi- og indeklimarenovering', *DANVAK*, p. 3. https://ipaper.ipapercms.dk/TechMedia/HVACMagasinet/2022/2/?page=60

In addition to the abovementioned publications, the Design Guide for I-DIFFER is attached to the Appendix.

DEPARTMENT OF THE BUILT ENVIRONMENT
AALBORG UNIVERSITY

Design Guide for I-DIFFER: The Double-Skin Facade Solution with Integrated Diffuse Ventilation

Olena Kalyanova Larsen
Chen Zhang
Lars Thomsen Nielsen
Mike Vinge Madsen
Sara Brøchner Bække
Gitte Thorup Tranholm
Ulrik Thomsen
Niels Kappel
Bent Atzen

ISSN 1901-726X
DCE Technical Report No. 317

Aalborg University
Department of the Built Environment
Energy and Buildings Research Group

BUILD Technical Report No. 317

Design Guide for I-DIFFER: The Double-Skin Facade Solution with Integrated Diffuse Ventilation

by

Olena Kalyanova Larsen
Chen Zhang
Lars Thomsen Nielsen
Mike Vinge Madsen
Sara Brøchner Bække
Gitte Thorup Tranholm
Ulrik Thomsen
Niels Kappel
Bent Atzen

December 2023

Scientific Publications at the Department of Civil Engineering

Technical Reports are published for timely dissemination of research results and scientific work carried out at the Department of Civil Engineering (DCE) at Aalborg University. This medium allows publication of more detailed explanations and results than typically allowed in scientific journals.

Technical Memoranda are produced to enable the preliminary dissemination of scientific work by the personnel of the DCE where such release is deemed to be appropriate. Documents of this kind may be incomplete or temporary versions of papers—or part of continuing work. This should be kept in mind when references are given to publications of this kind.

Contract Reports are produced to report scientific work carried out under contract. Publications of this kind contain confidential matter and are reserved for the sponsors and the DCE. Therefore, Contract Reports are generally not available for public circulation.

Lecture Notes contain material produced by the lecturers at the DCE for educational purposes. This may be scientific notes, lecture books, example problems or manuals for laboratory work, or computer programs developed at the DCE.

Theses are monograms or collections of papers published to report the scientific work carried out at the DCE to obtain a degree as either PhD or Doctor of Technology. The thesis is publicly available after the defence of the degree. Since 2015, Aalborg University Press has published all Ph.D. dissertations in faculty series under the respective faculty. The AAU Ph.D.-portal will host the E-books, where you also find references to all PhDs dissertations published from Aalborg University.

Latest News is published to enable rapid communication of information about scientific work carried out at the DCE. This includes the status of research projects, developments in the laboratories, information about collaborative work and recent research results.

Published 2023 by
Aalborg University
Department of the Build Environment
Thomas Manns Vej 23
DK-9220 Aalborg E, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No 317

Table of contents

Introduction

The I-DIFFER is the novel approach to renovate buildings quickly and subtly, particularly those like schools and offices with high internal heat load and ventilation needs. The I-DIFFER principle combines Double-Skin Façade (DSF) and Diffuse Ceiling (DC) ventilation using smart controls.

This guide aims to offer insights into key considerations for planning, designing, constructing, and operating I-DIFFER solution. In addition, the guide aims to inspire the adoption of the I-DIFFER solution in other projects. Whether you're an architect, engineer, or building manager, this document will support you in successful implementation of the I-DIFFER approach to improve energy efficiency, comfort and sustainability in your project.

The advices provided in this guide are rooted in practical experiences drawn from the I-DIFFER project and the collective wisdom of project partners. It is important for the reader to bear in mind that these recommendations are based on a limited number of cases. Thus, a careful consideration of the specific context and needs of your project must not be forgotten. For more information, please refer to publications, reports and guidelines included in the list of references.

The I-DIFFER project has received funding from the Energy Technology Development and Demonstration Program (EUDP), Denmark, under the name I-DIFFER (Journal number: 64020-2140).

Figure 1. Exterior façade before and after I-DIFFER renovation

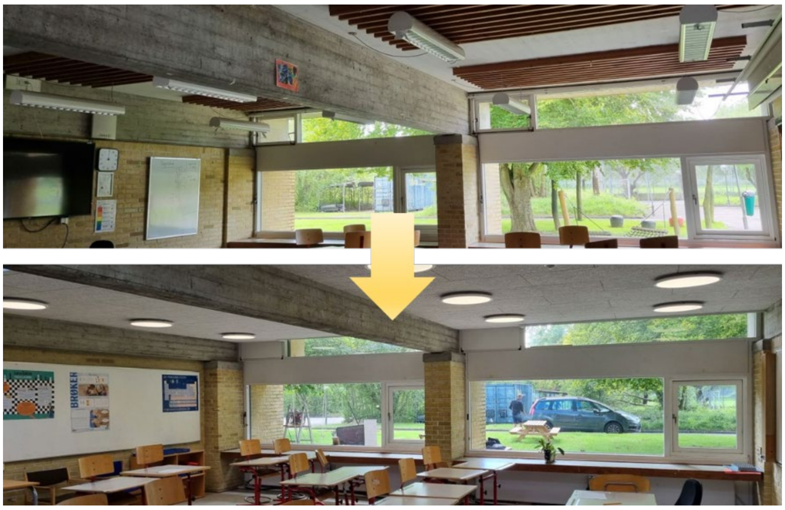

Figure 2. Room interior before and after I-DIFFER renovation

System description

Principles

Externally, an additional transparent (semi-transparent) layer is introduced to the pre-existing building envelope, forming what is known as a Double-Skin Façade (DSF). Internally, a diffuse ceiling (DC) is added for ventilation air supply without draught risk at low temperatures, *Figure 3*.

This integrated approach, complemented by mechanical exhaust in the room and intelligent control of airflow direction, ensures good air quality and energy efficiency. Operational modes are realized through the control of openings in the DSF.

Double skin facade

In warmer seasons, the DSF system can aid the reduction and removal of the solar heat gains in the occupied space. The reduction is due to solar radiation being captured in DSF before entering the room and then removed from DSF by natural ventilation. The heat removal is ensured by allowing air to bypass the facade and enter the diffuse ceiling directly from the outside, *Figure 4*.

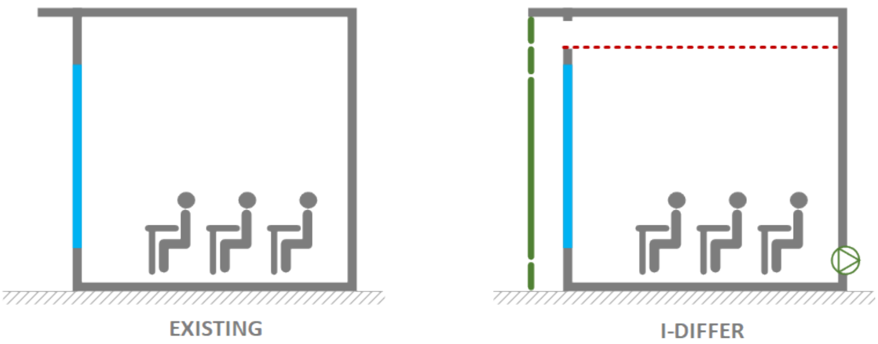

Figure 3. DSF and DC introduced to an existing building.

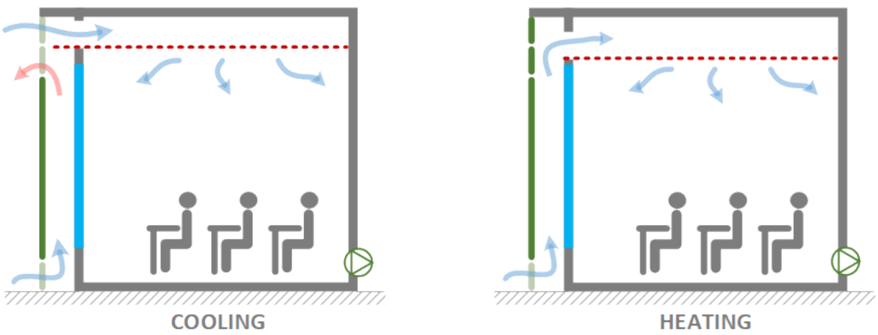

Figure 4. Key operational modes of I-DIFFER

Diffuse ceiling

DC ventilation utilizes suspended ceiling panels to deliver fresh air directly into occupied space. It effectively reduces draught risk by supplying low-momentum air, while minimizing the need for extensive ductwork and permitting the use of acoustic panels as air diffusers. In the hot season, DC ventilation through the bypass can facilitate the thermal mass activation, particularly when used for night cooling.

Control

The control system maintains optimal indoor conditions in the occupied space by adjusting the ventilation rate and managing the direction of heat gains and losses. This is achieved by coupling/decoupling the DC plenum and the double-skin façade. Additionally, the shading system in the DSF cavity can be integrated into the I-DIFFER control.

Design parameters

Orientation
The performance is optimal in South orientation. It is also efficient in the East and West orientations when evaluating comfort or the energy demand for heating. In North orientations, the solution maintains comfort, but the designer must anticipate a higher energy demand for heating, with consumption increasing by approximately 20 kWh/m^2 annually from South to North.

Glazing
For the additional exterior layer, opt for double glazing with a recommended U-value for the Insulated Glass Unit (IGU) up to 2.7 W/(m^{2}K). Ensure high light and solar transmission properties in the glazing to meet the visual comfort requirements for the room. Existing (interior) layer of glazing to remain unchanged.

Façade material
Maintain the current facade. While existing façade properties like density, thermal capacity, and shortwave reflection generally have a minor impact, a facade with substantial thermal mass will improve system dynamics, ease control, and reduce risk of overheating. Dark materials reduce heating demand but may increase the risk of overheating during a heatwave with sunny conditions.

Occupancy density
Apply this solution to buildings with high occupant density and/or substantial heat load (from 50 W/m^2 and above). It can ensure robust comfort and energy efficiency under increased occupancy density, provided the exhaust fan is appropriately sized. While comfort can be maintained with reduced occupancy, there might be a compromise in energy efficiency.

Depth of DSF
Due to construction, maintenance and safety considerations, it is likely that the depth of DSF will fall within the range of 0.8-1.2 meters.

Plenum design
DC plenum is the space formed above the DC panels. Plenum design involves definition of the plenum height, which must be at least 0.1 meters or more. The plenum must be at least 40% of the floor area to ensure effective distribution of supply air in the occupied space. Distribution of both active and passive DC ventilation panels should adhere to the guidelines outlined for DC ventilation. It is essential to pay special attention to ensuring sufficient sound absorption area while integrating lighting fixtures.

Room tightness
The I-DIFFER solution employs DC ventilation principles, utilizing the under pressure in the occupied space to direct the supply air to the DC and subsequently into the room. It is then extracted from the occupied space with the exhaust fan. In cases of leaky internal constructions and joints, it is recommended to opt for the pressurized method, where the exhaust fan is replaced by a supply fan, located in the interface between DSF and DC. Alternatively tightening of leakages in

the room must be done.

Fire safety

Evaluate whether the existing facade includes a fire escape exit. Conduct a thorough assessment of the possibilities for modifying the exit. The decision to preserve, relocate, or modify the exit significantly impacts the efficiency and feasibility of implementing the I-DIFFER solution. Refer to the demonstration project for a practical example of addressing this critical assessment on page 15.

Filtering of air

It is possible, and advisable to filter the air before entering the DC plenum to avoid the built-up of the dust. Refer to the demonstration project on page 15 for a practical example.

Noise

Noise from ventilation or moving components is not a concern for this solution. The acoustic properties in the room improve significantly due to high sound absorption efficiency of DC ventilation panels.

Custom-made elements

Custom-made elements may be necessary to implement I-DIFFER. These elements help reduce the number of moving parts, integrate replaceable air filters, or address fire escape openings. Refer to the demonstration project on page 15 for an example of how these elements are resolved.

Shading system

Buildings facing high solar exposure and a risk of overheating should incorporate a solar shading device. The optimal position for this device is within the DSF cavity, and the system performs best when the solar shading device is controlled automatically. Prioritize the use of reflective shading for optimal effectiveness. Consider integration of the guidelines for the indoor environment in schools (Vorre *et al.*, 2021).

Control

General
The ventilation system is stand-alone or BMS-integrated demand-controlled. If integrated, an automated two-way communication protocol between the ventilation system and BMS must be set-up to control windows, dampers, exhaust, shading and similar components if relevant. Additionally, it is recommended to facilitate remote support and operation of the ventilation system.

Controlled parameters
The indoor environment is controlled based on readings from the CO2 and temperature sensor, actual weather conditions—outdoor temperature, precipitation, wind speed, and temperature differences between outdoor, DSF cavity, DC plenum and indoors. Control of relative humidity is feasible, in line with CO2 control. Users must be given the possibility to override windows and shading controls, but the automation must ensure that the automated regulation is reactivated after a designated period.

Operational strategies
Two distinct operational strategies are suggested. One strategy for the space dominated by cooling demand (warmer seasons) and another for rooms with a predominant heating demand (cooler seasons) as in *Figure 4*. Each strategy incorporates several operational modes to cater to varying scales of heating and cooling demands. Consider a necessity of defining tolerance ranges for room temperature and CO2 levels to prevent the hysteresis effect. In case of rain and high wind speeds, the automatic control must ensure closing the openings in due time.

Night cooling
A distinctive feature of the I-DIFFER solution lies in its effective utilization of night cooling. Directly exposing the ceiling slab to supply air pathways in the plenum enhances thermal storage efficiency. During the night, heat stored in building structures is effectively removed, pre-cooling the environment for the following day. This not only smoothens but also shifts peak temperature occurrences. To ensure optimal efficiency, pay careful attention to the availability and exposure of thermal mass surfaces in the plenum, double facade, and within the room itself. Night cooling ventilation rate can be expected 200-250% of the capacity of traditional mechanical systems.

Visual comfort
For optimal performance, use of automated solar-shading control is compulsory for all buildings without natural shading (trees and shadows). Shading control must be coupled with the BMS system.

Implementation

Building selection

To determine the suitability of your building for the I-DIFFER solution, carefully evaluate the following criteria and decide accordingly.

Architecture. Evaluate potential architectural consequences for the building and its exterior appearance with the addition of the second skin. Evaluate its compliance with the local plan.

Outdoor environment. Confirm if outdoor air quality is suitable for direct supply in occupied spaces. Note that noise coming from outside will often not cause problems as the implementation of a double-skin facade and diffuse ceiling ventilation is very effective against noise.

Orientation of Spaces. Verify if dominant spaces are oriented towards the South, East, and West, as emphasized in the introduction.

Daylight Availability. Ensure there is an adequate daylight availability to allow the installation of the second skin while maintaining satisfactory daylight conditions. Availability of skylights in the building can support the implementation of I-DIFFER, without compromising the daylight conditions due to installation of DSF. Otherwise, the dispensation for compromised daylight conditions should be sought from the authorities.

Fire Escape Routes. Check for fire sections in the building and the existing fire escape routes in the building façade, considering potential additional costs if modifications are necessary to avoid potential spread of smoke or fire in the building.

Dimensions. Assess whether the dimensions of rooms and structures are sufficient for the installation of Double-Skin Façade and Diffuse Ceiling. In this step an evaluation of the roof construction for DSF installation, room height for DC installation, etc. are relevant to include.

Airtightness. Measure the airtightness of the building, including the internal partitions to ensure the feasibility of under-pressure ventilation.

Safety. Evaluate if the safety measures are necessary and possible to realize to avoid accidents related to the moving parts of the building envelope and the users, in particular children.

BR18

The I-DIFFER solution can both fall under the category of "modification" and "replacement" in Danish BR18 ('Bygnings reglamentet 18', 2018) [1]. The evaluation is made in each specific case for the façade element and ventilation. In the case of modification (as per §274), energy savings should be implemented if they are cost-effective and the requirements for renovation can be met by either complying with the individual requirements for all affected building components or by following the renovation classes outlined in §§ 280-282. Calculating the energy performance of the I-DIFFER solution in BE18 is not yet possible; hence, documentation according to the renovation classes requires more advanced tools such as Energy Plus, IDA-ICE, or others.

[1] BR18 effective as of January 2023.

In case the solution falls into category "replacement" of the ventilation system, then BR18 requirements in §447 must be satisfied, thus an acknowledged tool (Energy Plus, IDA-ICE, or others) can be used to document compliance of the primary energy use. If the need for primary energy is exceeded, it can be compensated for by other means.

Solution design, evaluation, and documentation

Evaluation of I-DIFFER solution performance potential (energy and comfort) is carried out and documented in two journal publications using IDA-ICE software (Bugenings *et al.*, 2022; Schaffer *et al.*, 2023). Reporting of the full-scale experimental performance evaluation (comfort) is available in another publication (Zhang *et al.*, 2023). Please refer to these documents for in-depth understanding of the system performance and the background for the guidelines provided in this report. For swift implementation of the solution, follow the guidelines provided in this report, but remember to assess the performance considering your specific case.

The energy use for heating and ventilation in the I-DIFFER solution is either lower or comparable to the traditional renovation approach provided that the design adheres to the guidelines. Moreover, enhancing system efficiency is possible by installing a heat pump to utilize the energy from warm exhaust air.

System performance related to energy and comfort can be thoroughly evaluated and optimized through dynamic building simulation tools. To ensure optimal performance, perform following assessments if relevant:

Ventilation capacity evaluation.

- Evaluate the required fresh air supply to maintain CO2 levels below specified thresholds.
- Assess the required outdoor air supply to cool the occupied space, especially during warmer seasons. Consider the incorporation of sufficient thermal mass, effective night cooling, and solar shading strategies to reduce maximum temperatures. The methodology described in SBi Anvisning 202 can be used unless an advanced simulation tool is used instead.
- Carefully evaluate the fan's capacity to meet fresh air demand (for cooling and CO2) without causing noise pollution in occupied spaces.

Sizing of DSF openings

- To prevent DSF overheating in warmer seasons, ensure proper ventilation by carefully sizing and positioning openings to outdoor.
  - o Estimate the required airflow to eliminate excess solar gains and to lower the DSF temperature to 4-8 degrees above outdoor temperature. A building simulation tool is advised for these calculations. Hand calculation using a heat balance can also be used.
  - o Size inlet and outlet openings to maintain air velocity below 2 m/s through the opening. Distribute openings evenly along the facade with at least 2.5 meters of vertical spacing between the bottom and top opening to enhance buoyant forces. Uneven distribution may result in inefficient DSF cooling due to unventilated dead zones.
  - o If needed, mitigate the risk of DSF overheating by integrating non-transparent façade elements at the bottom of the exterior skin or in areas that do not negatively impact daylight access into the occupied space.
- In cooling mode, be cautious of air short-circuits, where warm air from DSF enters the DC plenum, reducing the cooling potential of the system.
- Be aware of issues related to motorized openings, which may limit the size and degree of potential openings unless alternative methods are explored.

- During the cold season, an installed insulated damper can minimize airflow between the plenum and DSF during unoccupied periods, thereby reducing heat losses.

Daylight

- The daylight availability is reduced in I-DIFFER solution, and the degree of deficiency must be evaluated quantitatively by using a tool, suitable for the task for selection of optimal design proposal.

Assessment of sound quality and reduction of noise

- Ensure the sound absorption area is satisfactory by calculating the resulting sound absorption area in the space, accounting for active and passive diffuse ceiling panels. Note that the presence of in-built lighting fixtures reduces the available area for DC panel installation. Consider the use of circular lighting fixtures, as demonstrated in the demonstration building (on page 13). These fixtures provide added flexibility in DC design, not only in terms of sound absorption area but also for the distribution of active and passive panels in the ceiling.
- When placing a fan in the double-skin facade, the system should be designed with noise reduction in mind. It is recommended to insulate to prevent the fan noise from propagating into the occupied space. These noise reduction measures must be implemented to ensure compliance with the present requirements for technical installations in schools.
- Refer to the demonstration project on page 13 for an example of how the light fixtures and fan installation is resolved in the demonstration building.

Draught risk reduction

- Quantifying the risk of draught requires the use of computational fluid dynamics tools or detailed measurement. However, for ordinary classrooms or similar spaces, such calculations or measurements may be unnecessary if the guidelines for designing diffuse ceiling ventilation are adhered to (Zhang *et al.*, 2017). It is recommended to carefully place active and passive panels to ensure even air distribution in the entire space and avoid local air jet with high velocity penetrating the occupied zone. Special attention should be given to the placement of lighting equipment. It is recommended to place lighting under the passive panels.
-
- In practice, it is advisable to distribute active panels inward in the room to reduce the velocity of the cold air before its discharge into the occupied space. Smaller areas with evenly distributed active zones generally result in better air distribution compared to larger concentrated areas.

Safety

- Do not overlook safety measures essential for the secure operation of movable components in the I-DIFFER solution. Integrate grids and other automated features to prevent accidents. Do not overlook the fire regulations, both in terms of fire escape roots, but also the fire sections.

Architecture

- I-DIFFER solution can significantly influence the exterior appeal of the building. Thus, an integrated design which includes engineering and architectural analysis is advised through all of the process.

Building simulation tools

Energy Plus and IDA-ICE models for I-DIFFER solution were verified experimentally (Hu *et al.*, 2023; Schaffer, Bugenings and Larsen, 2023). Following are recommendations based on this work.

- Have a control strategy and the façade layout ready, as these elements are important in simplifying model geometry, a step necessary in most cases.
- Conduct model geometry simplification with an understanding of the control strategies to ensure that they can be realized in the model.
- Be aware that DSF-specific models within the software may not be suitable due to a lack of necessary control flexibility.
- Accurate definition of optical properties of constructions in DSF, as well as volumes of DSF cavity and DC plenum, are crucial for reliable results.

Different configurations of controllable openings for the I-DIFFER solution can be defined in building simulation models. The following examples illustrate how the openings, geometry and the model can be built in IDA-ICE and EnergyPlus software, respectively.

IDA-ICE

Opening (1) and (2) are modelled as window. Opening (3) is eliminated from the model and its function is covered by opening (2). Opening (5) is replaced by a leak (fixed flow) component in the roof. This is acceptable as IDA-ICE assumes perfect mixing and thus the location of the leak is not essential for the zone. Opening (4) is also modelled as a leak.

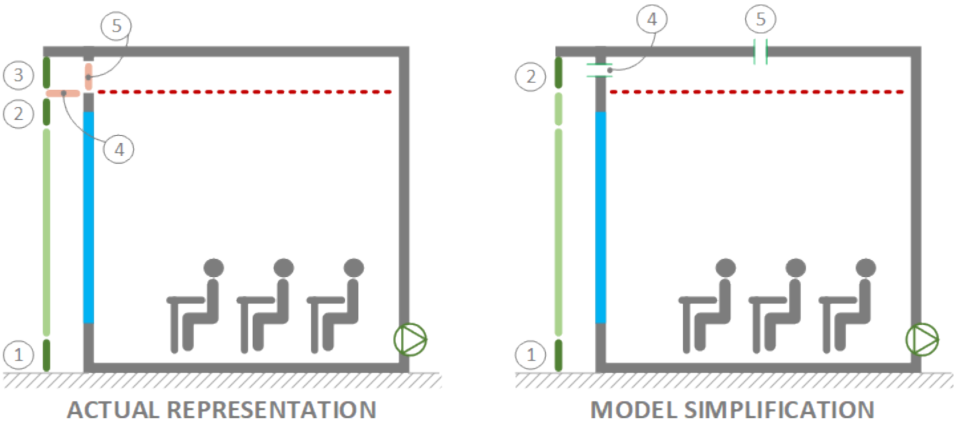

Figure 5. Example definition of openings in IDA-ICE.

The suggested model geometry simplification influences the height of the opening (2), which is critical for assessment of the buoyant forces and should be used with care. In this case also the preheating of air between openings (3)-(5) and (4)-(5) is not fully representable in the model, but can be considered as an acceptable simplification.

All thermal zones must be modelled with the detailed zone model (CeDetZon) of IDA-ICE.

EnergyPlus

In EnergyPlus the airflow is defined through the ventilation objects. For I-DIFFER, Zone Ventilation Object can be used to define the airflow directly from the outdoors to a thermal zone driven by a fan, as for example the airflow directly from the outside to the DC. This element is principally the same as the opening (5) in model simplification of IDA_ICE model, shown in *Figure 5*.

The Zone Mixing Object is used when the airflow goes between several zones. The Zone Mixing in EnergyPlus is a simple air exchange from one zone to another. Note that this statement only affects the energy balance of the "receiving" zone and will not produce any effect on the "source" zone. The use of airflow network is not necessarily beneficial for this type of problem.

Project realization

Most of the I-DIFFER solution can be executed externally, avoiding lasting disruptions to the interior spaces and occupants. Still, installing new ceilings (DC panels) is part of it, causing a brief disturbance (around 4-5 days per room). Thus, alternative spaces must be available during this time.

Consider implementing a trial installation. This will help identify critical or challenging aspects that can be discussed with the carpenter team, potentially leading to improvements for a more efficient, faster, or cost-effective installation.

Building service

Movable components in the double façade must be accessible for maintenance, including sensors, fans, motors, and the system filter.

The solution requires servicing for each individual classroom. A centralized system would involve fewer service points. However, external servicing makes it easier compared to planning maintenance inside the classrooms. Refer to the demonstration project on page 15 for an example of external access to the service point through DSF.

Costs

The I-DIFFER solution presents a robust alternative to traditional renovation methods. It eliminates the cost for traditional mechanical ventilation system (AHU, duct systems). It could use acoustics panels as air diffusers. Also a needed renovation of an existing façade, can be avoided with the new façade, that also can upgrade the architectural appearance of the façade. Nevertheless, the I-DIFFER approach can become more expensive due to the need for customization in each specific building. Its cost efficiency can be enhanced by adopting it as a modular plug-and-play system.

Future upgrade possibilities

While the above text covers the fundamental aspects of I-DIFFER design, following additional upgrade possibilities can be considered, if relevant:

- Transitioning from an exhaust system (air extracted by fan from the occupied space) to a supply system by relocating supply fan to the interface between the Double-Skin Facade (DSF) and Diffuse Ceiling (DC) plenum. This configuration change is demonstrated in the demonstration building (please refer to “Example of implementation” section).
- Integration of a filter within the system to prevent dust buildup in the DC plenum, as demonstrated in the demonstration building (please refer to “Example of implementation” section).
- Utilization of exhaust air from the occupied space in a heat pump for energy efficiency
- Preheating the plenum air using a heat pump, if necessary, for example for buildings with internal loads lower than advisable for this solution.
- For buildings requiring direct access to the outdoors (i.e. from the classroom) consider integration of such option, which can contribute in resolving challenges with integration of a fire access.
- Transforming I-DIFFER solution into a modular plug-and-play product will significantly reduce the need for customization in buildings of larger scale.

Example of implementation

The I-DIFFER solution underwent testing in a full-scale laboratory setup at Aalborg University and was subsequently implemented at Ellehøjskolen for demonstration purposes. The upcoming sections outline the implemented I-DIFFER solution in the school classroom.

Figure 6. Ellehøjskolen.

Pre-existing conditions

The classroom was naturally ventilated through the openings in the existing façade: 2 openings in the upper row of windows and two in the bottom row. The bottom openings also serve as fire escape routes from the classroom.

Facing South, the classroom features large window area, with natural shading from a tree, a generous overhang, and brick side constructions. The room has limited sound absorption, but benefits from substantial thermal mass in concrete beams and brick walls. Skylights positioned towards the North ensure even distribution of daylight across the room's depth, enhancing the overall daylight exposure.

Figure 7. Interior and exterior view of a classroom.

Specific system elements

<u>*System modulation*</u>

The architecture of the building and the layout of the classroom has imposed I-DIFFER system modulation, dividing the exterior façade and the plenum into two sections: Section Left and Section Right (*Figure 7*).

Figure 8. Interior view. Skylight in the classroom. Exterior façade.

<u>*Distribution of DC panels*</u>

Construction works started during summer school holidays, thus giving the priority to the internal works such as electrical works and installing DC panels. The distribution of active (shaded) and passive panels in the classroom, including lighting fixtures (circles) are shown in *Figure 9*. Notably, due to system modulation, the plenum is divided into Section Left and Section Right. The distribution of active panels in these two sections is intentionally different and therefore allows to assess user preferences to one or the other solution in the future.

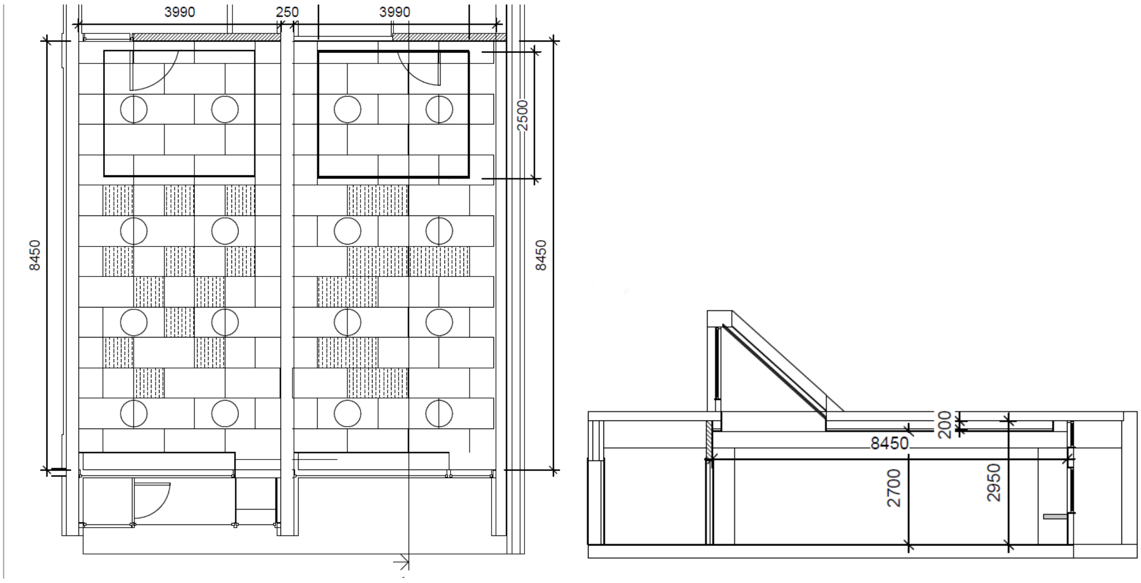

Figure 9. Plan and section of diffuse ceiling construction.

Fan location

Measurements of classroom's airtightness revealed significant leakage, making it impossible to implement DC ventilation in the traditional manner, by direct extraction of the air from the room. An alternative solution was developed. The fan is positioned in the interface between the DSF and the plenum rather than in the exhaust opening, see *Figure 10* below. This modification shifts the ventilation concept from an under-pressure to an over-pressure system.

Interface between DSF and DC plenum

An interface, to integrate a ventilation filter and the fan was developed. This interface also serves a purpose of supplying air to the DC plenum both directly from the outside or from the DSF. It is comprised of a box housing a fan and filter. The box is attached to the existing facade, and connected to the DC plenum through an existing opening (highlighted in yellow) as illustration in *Figure 10* below. Due to system modulation, one ventilation box is installed in Left Section and the other is in the Right.

Figure 10. The existing opening, highlighted in yellow and the ventilation box mounted to the existing façade (exterior and interior view).

The box is insulated, to minimize noise levels from the fan in the occupied area. Noise levels were measured at the highest airflow capacity 4000 m3/h to be below 30 dB. Additionally, a ventilation filter can be easily replaced through a dedicated opening on the side of the box, marked yellow in *Figure 11*.

Figure 11. Ventilation box: initial testing, construction, placement of the filter and installation in the DSF.

By-pass opening

The ventilation box serves as a dedicated bypass opening to supply the air directly from the outside to DC plenum. The bypass is activated when the control opens a dedicated window in the external façade. Once the window is open, it blocks all air access, except from the outside. An illustration below, *Figure 12* shows a window (heighted in green) that functions as damper. When the window is open, the bypass is activated. Otherwise, when the window is closed, the air to the ventilation box comes from the DSF cavity.

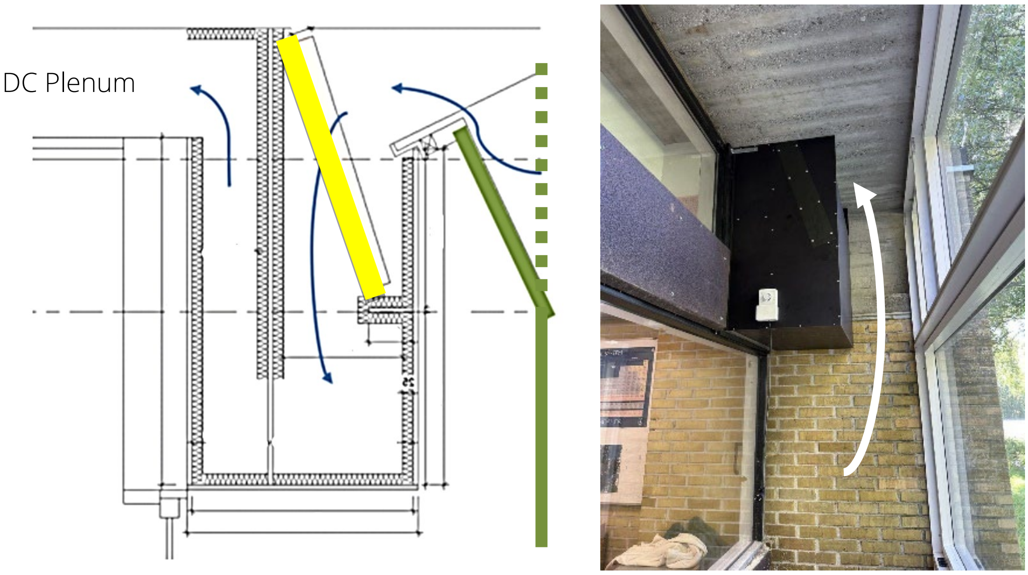

Figure 12. On the left: Cross-section of the ventilation box, with the by-pass window (green) open and the air movement directly from the outside through the ventilation box to the plenum. Filter is shown with yellow. On the right is the photo with the window closed and therefor all air intake is from DSF.

Fire escape

The fire escape openings were retained, and the DSF was extended to cover solely the fixed windows in each section of the façade, preventing any obstruction of fire escape openings. This resulted in small niches in each section, accommodating not only windows but also doors, as commonly found in schools. Moreover, it created the opportunity for discreet access for maintenance personnel to the DSF from outside, facilitating tasks like filter replacement, cleaning, and other maintenance requirements.

Figure 13. Preserved fire escape opening (inside and outside view). Access to DSF for maintenance.

Controlled openings

In each section of the facade, there are four openings that can be operated and controlled, these are highlighted in the *Figure 14*, below.

Inlet Openings: These openings allow air to enter the DSF. Openings are evenly distributed horisontally for optimal preheating. Ideally, they should be top-hang openings.
Outlet Opening: This opening is designed to discharge warm air from the DSF. Ideally, it should extend across the entire width of the facade to ensure even cooling down of the DSF.
Bypass Opening: This opening controls the ventilation strategy of the system, for more information please read about the by-pass opening above.

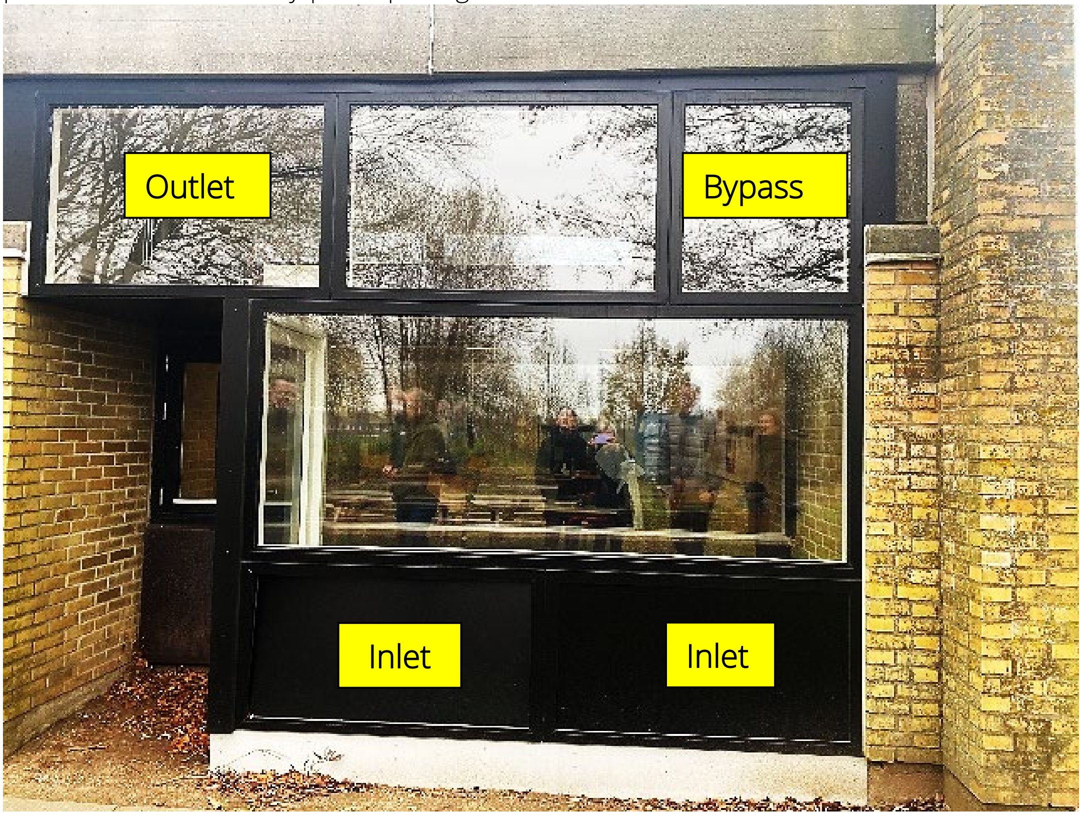

Figure 14. Controllable openings of the exterior façade.

Foundation

The DSF is mounted on screw foundations for simplicity.

Figure 15. Placement of screw foundation and selection of color palette.

Final solution

Interior view

The illustrations below (*Figure 16* and *Figure 17*) demonstrate the effective integration of circular lighting fixtures and the installation of DC panels, including a reduction in room height. It's noteworthy that the top row of windows has been preserved, made possible by positioning the panels at a distance from the facade. For additional details, please refer to the drawing showcasing the layout of DC panels.

Figure 16. Interior view: ceiling before.

Figure 17. Interior view: ceiling after.

<u>*Exterior view*</u>

Figure 18. Exterior view: before and after.

References

Bugenings, L.A. *et al.* (2022) 'A novel solution for school renovations: Combining diffuse ceiling ventilation with double skin facade', *Journal of Building Engineering*, 49, p. 104026. Available at: https://doi.org/10.1016/J.JOBE.2022.104026.

'Bygnings reglamentet 18' (2018). Trafik- Bygge og Boligstyrelsen. Available at: bygningsreglementet.dk.

Hu, Y. *et al.* (2023) 'Energyplus model of double skin façade and diffuse ceiling ventilation', *Journal of Physics: Conference Series*, 2600(6), pp. 1–6. Available at: https://doi.org/10.1088/1742-6596/2600/6/062003.

Schaffer, M. *et al.* (2023) 'Exploring the potential of combining diffuse ceiling and double-skin facade for school renovations', *Building and Environment*, 235, p. 110199. Available at: https://doi.org/10.1016/J.BUILDENV.2023.110199.

Schaffer, M., Bugenings, L.A. and Larsen, O.K. (2023) 'Validating a Building Performance Simulation Model of a naturally ventilated Double Skin Facade', *Journal of Physics: Conference Series*, 2654(1), p. 012092. Available at: https://doi.org/10.1088/1742-6596/2654/1/012092.

Vorre, M.H. *et al.* (2021) *Branchevejledning for indeklima i skoler - Teknologisk InstitutVorre*. 1st edn. Branchevejledning for indeklima i skoler. Available at: https://www.teknologisk.dk/branchevejledning-for-indeklima-i-skoler/43383 (Accessed: 3 January 2024).

Zhang, C. *et al.* (2017) 'Diffuse Ceiling Ventilation: Design Guide for Wood Wool Cement Panel'. Department of Civil Engineering, Aalborg University. Available at: https://vbn.aau.dk/da/publications/diffuse-ceiling-ventilation-design-guide-for-wood-wool-cement-pan (Accessed: 3 January 2024).

Zhang, C. *et al.* (2023) 'Experimental investigation of an integrated renovation solution combining diffuse ceiling ventilation and double skin façade', *Building and Environment*, 246, p. 111000. Available at: https://doi.org/10.1016/j.buildenv.2023.111000.

SBi-Anvisning 202 Naturlig ventilation i erhvervsbygninger. Statens Byggeforskningsinstitut, 2002.

ISSN 1901-726X
DCE Technical Report No. 317

ISSN 1901-726X
DCE Technical Report No. 321