JOURNAL OF FACADE DESIGN & ENGINEERING

VOLUME 6 / NUMBER 3 / 2018

SPECIAL ISSUE

FAÇADE 2018 – ADAPTIVE!

EDITORS IN CHIEF ULRICH KNAACK AND TILLMANN KLEIN
GUEST EDITORS ANDREAS LUIBLE, LAURA AELENEI, MARCO PERINO, FRANK WELLERSHOFF AND UTA POTTGIESSER
SUPPORTED BY THE EUROPEAN FACADE NETWORK

JOURNAL OF FACADE DESIGN & ENGINEERING

VOLUME 6 / NUMBER 3 / 2018

EDITORS IN CHIEF ULRICH KNAACK AND TILLMANN KLEIN
GUEST EDITORS ANDREAS LUIBLE, LAURA AELENEI, MARCO PERINO, FRANK WELLERSHOFF AND UTA POTTGIESSER
SUPPORTED BY THE EUROPEAN FACADE NETWORK

SPECIAL ISSUE

FAÇADE 2018 – ADAPTIVE!

JFDE Journal of Facade Design and Engineering

JFDE presents new research results and new proven practice of the field of facade design and engineering. The goal is to improve building technologies, as well as process management and architectural design. JFDE is a valuable resource for professionals and academics involved in the design and engineering of building envelopes, including the following disciplines:

- – Architecture
- – Building Engineering
- – Structural design
- – Climate design
- – Building Services Engineering
- – Building Physics
- – Design Management
- – Facility Management

JFDE will – initially - be directed at the scientific community, but it will also feature papers that focus on the dissemination of science into practice and industrial innovations. In this way, readers explore the interaction between scientific developments, technical considerations and management issues.

Publisher
TU Delft Open
TU Delft / Faculty of Architecture and the Built Environment
Julianalaan 134, 2628 BL Delft, The Netherlands

Contact
Thaleia Konstantinou
JFDE-BK@tudelft.nl
+ 31 (0)6 48 27 26 43
http://jfde.tudelft.nl/

Policies
Peer Review Process – The papers published in JFDE are double-blind peer reviewed.
Open Access – JFDE provides immediate Open Access (OA) to its content on the principle that making research freely available to the public supports a greater global exchange of knowledge.

Indexation – JFDE is indexed in the Directory of Open Access Journals (DOAJ), Google Scholar, Inspec IET and Scopus.
Publication Ethics – Editors, authors and publisher adopt the guidelines, codes to conduct and best practices developed by the Committee on Publication Ethics (COPE).

Design & layout
Design – Sirene Ontwerpers, Rotterdam
Layout – Nienke Blaauw, TU Delft

ISSN 2213-302X (Print)
ISSN 2213-3038 (Online)
ISBN 978-94-6366-099-0

Submissions
All manuscripts and any supplementary material should be submitted to the Editorial Office (JFDE-BK@TUDelft.nl), through the Open Journal System (OJS) at the following link: http://jfde.tudelft.nl/

Author Guidelines
Detailed guidelines concerning the preparation and submission of manuscripts can be found at the following link:
https://journals.open.tudelft.nl/index.php/jfde/about/submissions

COST TU1403
fn/Adaptive facades network

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the Horizon 2020 Framework Programme of the European Union

TU Delft open Journals

Contents

Editorial

This special issue is linked to the conference FAÇADE 2018 – Adaptive!, the fifth conference that has been organised by Lucerne University of Applied Science and Arts within the framework of the European Façade Network, EFN. FAÇADE 2018 is also the final conference of the COST Action TU1403 'Adaptive façades network' (www.tu1403.eu) and dedicated to multifunctional, adaptive, and dynamic building envelopes.

Approximately one third of all energy consumed by end-users in Europe today is for space heating& cooling, ventilation, and lighting of buildings. Therefore, the energy performance of future building envelopes will play a key role in meeting the EU's climate and energy sustainability targets. While most of our façades today are passive systems and are largely exhausted from an energetic point of view, multifunctional, adaptive, and dynamic façades can be considered as the next big milestone in façade technology. Adaptive building envelopes are able to interact with the environment and the user by reacting to external influences and adapting their behaviour and functionality accordingly: the building envelope insulates only when necessary, it produces energy when possible, and it shades or ventilates when the indoor comfort so demands. Nevertheless, the development and realisation of adaptive building envelopes is still in the initial stages.

In order to advance the development and application of adaptive façades, COST Action TU1403 'Adaptive Façades Network' was initiated in 2014. The COST Action, which started in 2015 and will end in late 2018, is a European research project with the objective to support trans-national cooperation between researchers and industry through science and technology networks. Over four years, more than 210 participants from 27 countries were involved in numerous COST networking activities: 15 meetings, two training schools, two industry workshops, 31 short term scientific missions, and two conferences.

The main objectives of the COST Action were to:

- increase knowledge sharing between the various European research centres and between these centres and the industry;
- foster the development of novel concepts and technologies and/or new combinations of existing technologies for adaptive façades;
- foster the development of effective evaluation tools, methods, and metrics for adaptive façades.

The work was managed in four working groups:

- WG1. Adaptive technologies and products
- WG2. Component performance and characterisation methods
- WG3. Whole building integration and whole-life evaluation methods of adaptive façades
- WG4. Dissemination and future research

The more than 60 presentations and proceeding contributions at the conference FAÇADE 2018 are the result of COST TU 1403 and give an overview of the state of the art in adaptive façade technology. The thirteen articles in this Special Issue FAÇADE 2018 – Adaptive! were proposed by the guest editors, who are working group (WG) leaders, and the scientific committee to undergo the double-blind peer review process of JFDE. The criteria for the selection of papers from proceeding contributions were the completeness of work and the scientific relevance, so that the special issue constitutes a representation of the work executed by the Action's working groups.

As guest editor, I would like to thank the authors and reviewers for their significant contributions to this special issue. Moreover, I sincerely thank Susanne Gosztonyi and Stephanie Ly-Ky for their great assistance during the whole process. I also want to thank COST (European Cooperation in Science and Technology). This special issue is based upon work from COST Action Tu1403, supported by COST. Last but not least, constructive comments and great help of the JFDE editor Thaleia Konstantinou, and Editors in Chief, Ulrich Knaack and Tillmann Klein, are gratefully acknowledged.

Andreas Luible - Chair of COST Action TU1403

This special issue is based upon work from COST Action TU1403 'Adaptive Façades Network', supported by COST (European Cooperation in Science and Technology).

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, careers, and innovation.

Funded by the Horizon 2020
Framework Programme
of the European Union

Post-Occupancy Evaluation for Adaptive Façades

Shady Attia[1*], Alessandra Luna Navarro[2], Miren Juaristi[3], Aurora Monge-Barrio[3], Susanne Gosztonyi[4], Zein Al-Doughmi[5]

* Corresponding author
1 Sustainable Building Design Lab, Department UEE, Faculty of Applied Sciences, University of Liege, Belgium, shady.attia@uliege.be
2 University of Cambridge, UK,
3 Universidad de Navarra, School of Architecture, Spain
4 Lucerne University of Applied Sciences and Arts, Engineering and Architecture, Switzerland
5 Cardiff University, UK

Abstract

Post-occupancy evaluation is a valuable method of generating information on the performance of adaptive building façades in relation to users. This evaluation technique involves both procedural methods, such as soft-landing, and empirical measuring, such as environmental monitoring or self-reporting techniques including surveys. Several studies have been carried out in recent decades to identify the most appropriate methods for occupant comfort, well-being, productivity, satisfaction, and health assessments in workplaces. Post-occupancy evaluation of adaptive façades can, however, be a challenging task and information on this topic is still scarce and fragmented. The main contribution of this paper is to bring together and classify the post-occupancy evaluation methods for adaptive façades and suggest a framework for their holistic evaluation. Specific recommendations for improving current standards and guidelines are outlined here to enhance occupant satisfaction and environmental conditions in workplaces for future design projects. Finally, we discuss various ongoing trends and research requirements in this field.

Keywords

advanced façades, user interaction, measurement, surveys, criteria, framework, indoor comfort

DOI 10.7480/jfde.2018.3.2464

1 INTRODUCTION

As we continue to innovate and build energy efficient and advanced façades that are automated, we are looking forward towards the optimisation of the overall work, living, and learning experience indoors. Traditionally, Post-Occupancy Evaluation (POE) was used to assess the users' experience in relation to outdoor and indoor environments. However, POE for Adaptive Façades (AF) (Loonen, Trčka, Cóstola, & Hensen, 2013)due to a growing demand to satisfy more ambitious environmental, societal and economical performance requirements. The application of climate adaptive building shells (CABS requires a specific approach of obtaining feedback about users' experience and building performance in use. POE for AF includes investigating occupants' interactions with the envelope and the overall building performance regarding energy efficiency, indoor environmental quality (IEQ), and occupants' satisfaction, well-being, and productivity. This paper is part of the COST Action TU 1403 on AF and aims to provide an overview of existing and expected POE assessment methods. As part of Work Group 3, previous work has introduced adaptive façades systems assessment (Attia Favoino, Loonen, Petrovski, & Monge-Barrio, 2015; Attia et al., 2019) and reviewed case studies (Attia & Bashandy 2016; Attia, 2017; Bilir & Attia, 2018) of adaptive façades in which POEs were performed. However, there is a lack of comprehensive POE for AF that provides both qualitative and quantitative assessment and more importantly, involves users, designers, and building operators. The nature of adaptive façades that are able to adapt to changing climatic conditions on a daily, seasonal, or yearly basis requires different assessment and evaluation methods. The transient and dynamic behaviour of those façades make them a particular building technology that is novel and without precedent in terms of systematic assessment frameworks and approaches. Therefore, in this paper we present a short introduction to AF and POE. Then, we present a brief literature analysis of three POE projects for AF, assessed to show the challenges and requirements of AF assessment. This includes summarising and comparing key POE assessment. In Section 4, we propose an initial assessment framework and a discussion on the direction for future POE in Section 5.

2 BACKGROUND OF ADAPTIVE FAÇADES AND POST-OCCUPANCY EVALUATION

A major challenge in respect to AFs is the evaluation of their responsiveness to climate and occupants needs. The defining characteristics of AF systems is their dynamic adaptability and multi-usability of their components. Some of them take over certain tasks to change the thermal, visual, or hygienic comfort situation. The influence of, for example, dynamic measures for thermal comfort on the user's perception requires target criteria other than standardised comfort models (EN ISO 7730:2005) (ASHRAE, 2013). The topic "thermal sensation and perception of humans", including the phenomenon alliesthesia (de Dear, 2014) – a physiological approach on how pleasant or unpleasant stimuli can influence the thermal comfort perception of humans – needs to be introduced. This could lead to a "'responsive' standard that acknowledges the richness of human-environmental interaction and the potential for less energy-intensive design" (de Dear, 2011).

The dynamic behaviour of adaptive façades requires the continuous or high frequency data gathering from occupants to capture their response to transient changes in the properties of adaptive façades. Adaptive façades can have different effects on occupants depending on the initial and final state of their adaptive process, as well as on the velocity and frequency of change. For instance, occupant response to automatic shading controls significantly changes if the system is lowering or raising the shading devices (Reinhart & Voss, 2003). Bakker, Hoes-van Oeffelen, Loonen, and

Hensen (2014) also showed that less frequent, discrete transitions in façade configuration are more acceptable to users than smooth transitions at a higher frequency. Traditional POE methods do not allow real-time data gathering or transient assessment of adaptive buildings, and occupants are usually asked to "remember" their comfort state in surveys or interviews (Buratti & Ricciardi, 2009) or to record their comfort state in diaries, thereby undoubtedly losing important information on dynamic environmental changes and their effect on users. Occupant satisfaction with personal control of, and interaction with, adaptive façades is also a time-dependent feature. Examples of this are the changing levels of user acceptance for automatic strategies and expectations for personal control with time. In this sense, Ball and Callaghan (2012) presented an "adjustable autonomy system", in which levels of control were gradually increased as the user gained confidence in using the interactive system.

Another challenge of AF assessment is related to the time of assessment. POE comes at a late stage of the façade's delivery process. POE starts with the operation stage, at the end of commissioning of newly or renovated buildings. As shown in Fig.1, the life cycle of AF is long and does not require an on-off POE, but rather a continuing POE, at least for the time required to assess the range of the façade´s adaptability. The nature of AF requires that POE are adapted to become transient and frequent to match the control strategies, trace occupants response actions and the AF response or action. The automatic control of AF and users' response is, in many cases, conflicting (Bilir & Attia). From one side, building operators control building systems to ensure good IEQ and achieve energy efficiency, and on the other hand, building occupants are seeking localised control of their specific working, living, or learning environment. The conflict between the local and global spatial IEQ and manual versus automated control of AF makes the POE difficult. As learned from several case studies of AF (Bilir & Attia, 2018) there is a lack of comprehensive POE to cater for AF and empower users while assuring control by building operators during the AF's life cycle. This conflict requires continuous feedback and flexible building management systems and control software. Historically, operators are responsible for the control of building systems. However, the awareness about well-being and occupant's feedback, and the proliferation of low-cost sensors and interactions devices, requires a modern approach to manage this complex problem. The operation of AF requires that users are central and that a building management system (BMS) does not only respond to the operators. There is a need to create a balance between running the façades actuators and responding to user's needs.

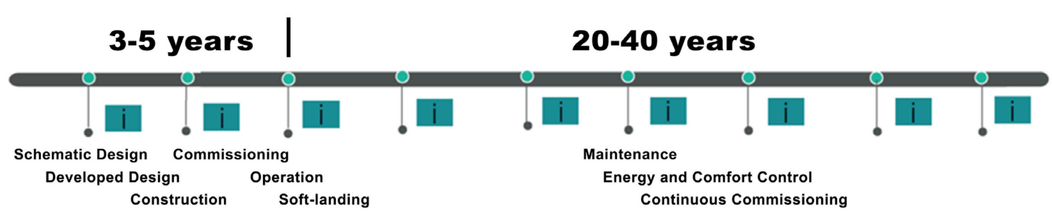


FIG. 1 Adaptive Façade life cycle

3 CURRENT POE METHODS

There are several extensive literature reviews that investigated POE (Preiser, 1995, 2005; Leaman & Bordass, 2001; Bordass & Leaman, 2005; Meir, Garb, Jiao, & Cicelsky, 2009; Pati & Pato, 2013; Kim, de Dear, Candido, Zhang, Arens, 2013; Galatioto, Leone, Milone, Pitruzzella, & Franzitta, 2013; Li, Froese, & Brager, 2018). Preiser (1995) classified three levels of POE: 1) indicative, 2) investigative, and 3) diagnostic. This classification focused on grouping POE methods based on their purpose. However, the most common classification of POE methods is based on grouping them as follows (Li et al., 2018):

- Subjective or Qualitative Methods: 1) Occupants Surveys, 2) Interviews, and 3) Walkthroughs.
- Physical Quantitative Methods: 1) IEQ in situ measurements and 2) energy and water audits and monitoring

Based on our literature review, we identified POE methods that follow a systematic methodology to examine the overall performance of the building. Table 1 provides a brief comparison of the three existing POE methods that were strongly present in the practice.

POE METHOD	YEAR	COUNTRY	ASPECTS EVALUATED
1 Post-Occupancy Review of Building Engineering (PROBE) Building Use Studies (BUS)	1995	UK	BUS occupant survey, benchmarking against an existing database of case studies (Leaman & Bordass, 2001)
2 Center of Built Environment (CBE) Building Performance Evaluation (BPE) toolkit	2003	US	Occupant IEQ satisfaction survey with a score card report generation tool. CBE Thermal Comfort tool to calculate thermal comfort according to ASHRAE Standard 55 (Zagreus, Huizenga, Arens, & Lehrer, 2004)
3 Performance Measurement Protocol	2010	US	Energy and water use and IEQ. Comprises three levels of evaluation. Three levels—Basic (indicative), Intermediate (diagnostic), and Advanced (investigative) (ASHRAE, 2010).
4 ASHRAE 55 Comfort Survey	2001	US	Comfort conditions are measured based on a survey (ASHRAE, 2013).

TABLE 1 Comparison of current POE methods used frequently in practice

Based on our review of POE methods and their suitability for AF evaluation in relation to user satisfaction, we identified emerging limitations inherent in the current POE methods. These limitations, related to POE for AF, can be summarised under the following points:

- Current POE methods do not allow real-time data gathering and transient assessment, which are fundamental to capturing and verifying the dynamic performance and degree of responsiveness of adaptive façades.

- Current methods focus on comfort in relation to the occupant's response and control. They are unable to assess the interaction between the user and the AF in transient terms.

- Current POE methods do not identify the moment of dissatisfaction. Rather, they provide an overall assessment based on a seasonal or annual evaluation and do not allow for the capturing of the effects of AF change at a specific time.

- Researchers and building experts cannot associate or distinguish occupants' interaction and behaviour from the overall environmental impact of AF, likewise in relation to BMS.

- Most of the time, POE outcomes are not fed back to inform the operator. The feedback loop is linear and not circular. Simultaneously, there is a lack of continuous feedback that would allow occupants to respond to energy efficiency or comfort improvement measures during hours of operation. Closing the information loop is also fundamental to allowing a dynamic POE, which is crucial to train and adjust AF control strategies in order to meet or predict actual occupant demands.

- Researchers and building experts don't have a benchmark for AF to compare with the traditional POE of buildings database. The majority of POEs are heavily customised to better assess the building behaviour, but this essential in AF, since they are generally innovative envelopes designed with a specific purpose.

From our current review, we can state that there is, at present, a knowledge gap and a challenge in assessing AF using POE methods. There is a serious need for POE methods that can assess the engagement and overall well-being and productivity of occupants. There is a need to redesign POE methods that focus on the interplay between technology, the user in the physical space, and building operator. At last, since AF are generally new systems and materials, POE (following previous assessment and validation of the adaptive system itself) will provide a further support for their implementation in the building sector.

4 FUTURE POST OCCUPANT EVALUATION METHOD FOR ADAPTIVE FAÇADES ASSESSMENT

In this section, we present a framework for future POE for AF and suggest a User Interface (UI) for a dynamic online use. Furthermore, we suggest some key recommendations for future POE for AF.

We identified the main components that future POE of AF should incorporate, based on our literature review and experience with POE, which was performed for three AF case studies (Attia & Bashandy, 2016; Attia, 2017; Bilir & Attia, 2018). Additionally, as part of TU 1403 COST Action, in Work Group 3 we developed a façade assessment framework for dynamic post-occupancy evaluation. As shown in Fig. 2, the proposed framework allows multiple users, mainly occupants and operators, to share the management and control of the indoor environment and the adaptive façades technology. In this sense, the framework allows instantaneous feedback involving the users and operators in a dynamic and integrated way. Our framework suggests transforming POE into a dynamic and interactive process. The developed framework focuses on energy savings, maintenance savings, control strategies, and productivity and user experience. The framework depends mainly on a central control point that connects users and operators through BMS. Future POE should be based on a platform that receives direct and continuous feedback from the indoor environment, and likewise from the façade system. With the help of BMS, it is expected that a predictive model control with overriding control by the users can better assess the situation as frequently as the adaptability of the façade suggests, and perform a continuous automated POE assessment. It must always be kept in mind that the active interaction of the user is only accepted as and when necessary, since users prefer to be comfortable and feel productive without being aware of the controls, only interacting occasionally (Buckman, Mayfield, & B.M. Beck, 2014).

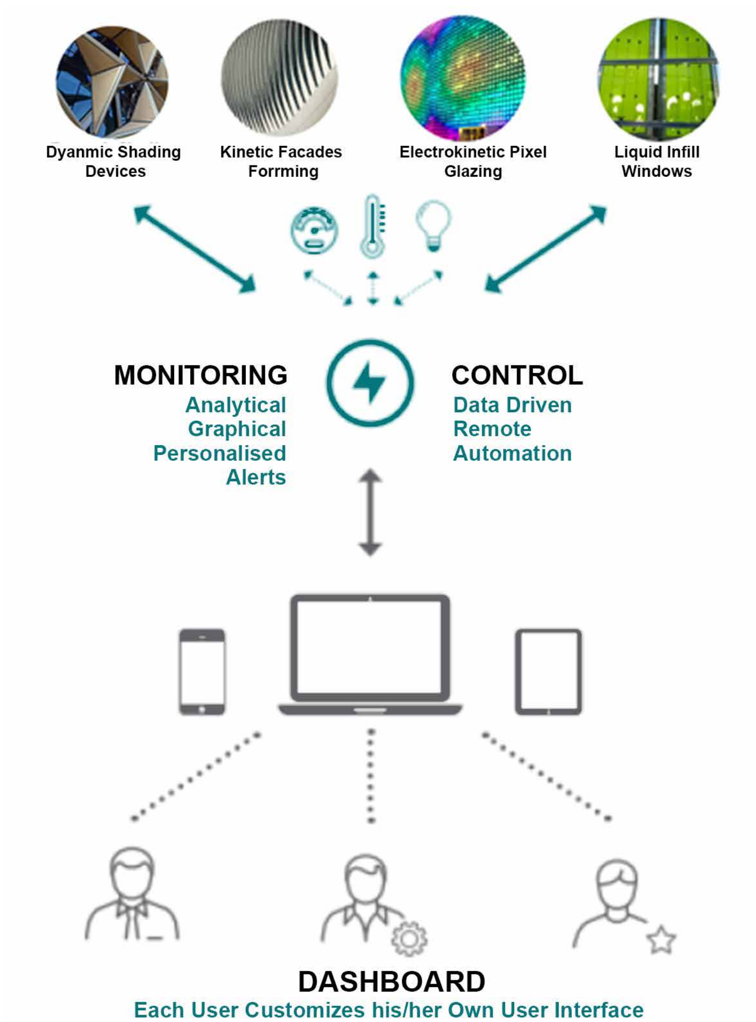


FIG. 2 Adaptive Façade framework for dynamic post-occupancy evaluation

Next, we developed a scheme in the form of a dashboard with a UI that can be used by smart devices or personal computers. The idea of this dashboard scheme is to encourage future studies and research in the area of POE to embrace instant feedback. Historically, the loop of cause and effect was distant in time. However, the advances in IT and sensor technology requires a revolutionary approach for POE. As shown in Fig. 3, the UI provides real time feedback for comfort and energy performance (right). At the same time, the UI allows for the interaction between users and the building operator (left) through alarm messages or modification requests. The satisfaction of users in relation to the façade performance can be directly reported to facility managers. In this sense, users maintain better control on their indoor environment and their façade's adaptive technology. We expect that such a UI is the front end of a complex BMS and platform that integrates advanced control, intelligent algorithms, and actuators that allow the active management of the façade response, thereby providing value to occupants, building operators, and building owners.

Lastly, based in our experience of the COST Action TU1403, we would like to recommend a series of new questions to be added to future POE surveys as they relate to a building with AF (Attia, Bilir & Safy, 2018). As Li et al. (2018) conclude in their review, occupant satisfaction is the most common focus and occupant surveys the most frequently used method in POEs. The following recommendations should be included in surveys:

- Are you aware of the adaptability of your façade?
- Are you comfortable with the adaptability?
- Are you satisfied with your ability to control your façade?
- How often would you like your façade to change?
- Do you think that your façade contributes to the improvement of the thermal characteristics of your workplace/space?
- Do you think that your façade contributes to the improvement of the luminous characteristics of your workplace/space?
- Do you think that your façade contributes to the improvement of air quality in your workplace/space?
- Do you think that your façade contributes to ensuring a satisfactory acoustic environment in your workplace/space?

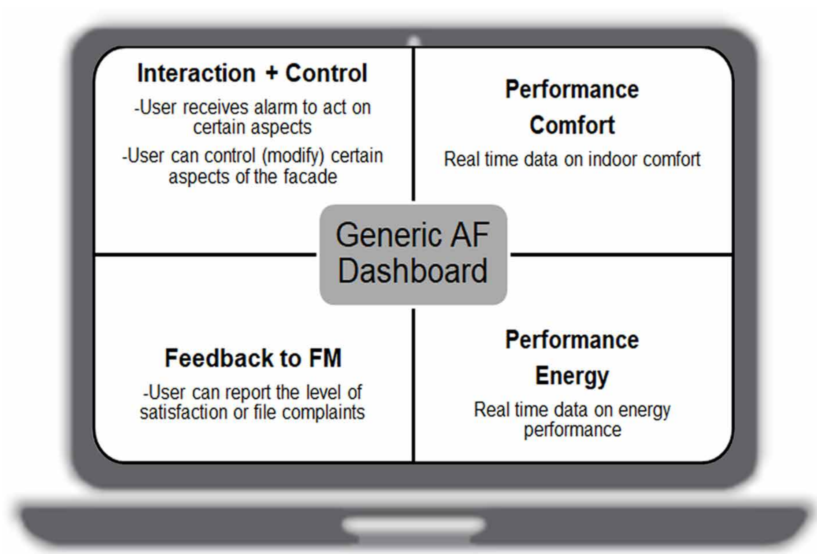


FIG. 3 Adaptive Façade control and feedback dashboard

5 DISCUSSION AND CONCLUSION

There is a market trend for health and well-being within our Architectural, Engineering, and Construction (AEC) industry (Attia, 2019). As we continue to humanise the experience of our working, living and learning places, AFs are advanced and dynamic systems that have the potential to support life quality and people's well-being and productivity in a resource-efficient manner. In this paper, we reviewed the current literature and identified the need for continuous monitoring and interactive control to benchmark the effectiveness of AF. We found that several challenges and implications that have been previously reported in literature hinder the use of POE for AF. Most importantly, there is a very little uptake of POE from the façade industry and an imbalanced focus on the aesthetic aspects of AF.

AF requires a closed loop of dynamic and instantaneous feedback to address the complexity of IEQ, HVAC systems performance, and occupant satisfaction. POE should be able to assess the availability of a range of user or operator control choices and their effectiveness in relation to HVAC and AF system characteristics. Different control objectives in buildings with AF can also work in opposition to each other. Building operators and owners require tools and user interfaces that can locate and report upon occupants experience behind facades. There is a need for tools that empower users and help to solve those potential conflicts in AF operation and interaction between occupants, façade systems, and other HVAC components.

Therefore, there is a serious need to use test facilities and simulation-based approaches that can help building operators to test, compare, and improve POE methods and, consequently, optimise AF supervisory control strategies based on a variety of metrics. Novel and effective POE methods for AF are also fundamental to allowing optimal façade responsiveness in time and, potentially, providing a means for enabling the modelling of predictive control strategies. Lastly, the future of POE of AF should be based on user experience. User experience is a key factor in the success of POE methods and a fundamental step towards the successful uptake of AF in the construction industry. Future research, therefore, should focus on developing novel metrics to capture user experience of AF.

Our findings can be useful for researchers in identifying new and industry-relevant research areas and for practitioners to learn from empirically investigated challenges in POE, and base their improvement efforts on such knowledge. Identifying and investigating the overlaps underline the importance of these challenges, and can also help in finding other research areas, not only for enhancing POE for AF, but also for BMS and control software quality in general. It also makes it easier for practitioners to spot, better understand, as well as find mitigation strategies for POE for AF, through learning from past experiences and developments in the area of user experience and feedback quality.

Acknowledgements

The authors appreciate the survey respondents' valuable comments and feedback. The author would like to gratefully acknowledge COST Action TU1403 "Adaptive Façades Network" for providing excellent research networking. The authors would like to acknowledge the support of Work Group 3 members.

References

ASHRAE (2010). *Performance measurement protocols for commercial buildings*. American Society of Heating Refrigeration and Air Conditioning Engineers. Inc., Atlanta.

ASHRAE (2013). *55: Thermal Environmental Conditions for Human Occupancy*. American Society of Heating Refrigeration and Air Conditioning Engineers. Inc., Atlanta.

Attia, S., Favoino, F., Loonen, R., Petrovski, A., & Monge-Barrio, A. (2015). Adaptive Façades System Assessment: An initial review. *10th Conference on Advanced Building Skins, 3-4 November*, 1265-1273, Bern, Switzerland.

Attia, S. & Bashandy, H. (2016). Evaluation of Adaptive Façades: The Case Study of AGC Headquarter in Belgium. In Belis, Bos, & Louter (Eds.) *Challenging Glass 5 – Conference on Architectural and Structural Applications of Glass*. Ghent University, Belgium, ISBN 978-90-825-2680-6.

Attia, S. (2017). Evaluation of adaptive façades: The case study of Al Bahr Towers in the UAE. *Shaping Qatar's Sustainable Built Environment*, Hamad Bin Khalifa University Press, Volume 2, Issue 6, P1-13.

Attia, S. (2018). Challenges and Future Directions of Smart Sensing and Control Technology for Adaptive Façades Monitoring. *Next Façades COST Action TU1403 Adaptive Façades Network Conference*, Lucerne University, 26-27 November 2018. Lucerne, Switzerland.

Attia, S., Bilir, S., & Safy, T. (2018) *Adaptive Façades performance assessment: Interviews with Façade Experts*, SBD Lab, Liege University, Belgium. ISBN: 9782930909097. Retrieved from https://orbi.ulg.ac.be/handle/2268/213736.

Attia, S., Bilir, S., Safy, T., Struck, C., Loonen, R., & Goia, F. (2018) Current Trends and Future Challenges in the Performance Assessment of Adaptive Façade Systems. Energy and Building, in Press.

Ball, M., & Callaghan, V. (2012, June). Explorations of autonomy: an investigation of adjustable autonomy in intelligent environments. In Intelligent Environments (IE), 2012 8th International Conference on IEEE. (pp. 114-121).

Bakker, L. G., Hoes-van Oeffelen, E. C. M., Loonen, R. C. G. M., & Hensen, J. L. M. (2014). User satisfaction and interaction with automated dynamic facades: A pilot study. Building and Environment, 78, 44-52.

Bilir, S., Attia, S. (2018). Performance Evaluation of Adaptive Façades: A case study with electrochromic glazing. *Next Façades COST Action TU1403 Adaptive Façades Network Conference*. Lucerne University, 26-27 November 2018. Lucerne, Switzerland.

Bordass, B., & Leaman, A. (2005). Making feedback and post-occupancy evaluation routine 1: A portfolio of feedback techniques. *Building Research & Information*, 33(4), 347-352.

Buckman, A. H., Mayfield, M., & B.M. Beck, S. (2014). What is a Smart Building? *Smart and* Sustainable Built Environment, 3(2), 92–109. https://doi.org/10.1108/SASBE-01-2014-0003

Buratti, C., & Ricciardi, P. (2009). Adaptive analysis of thermal comfort in university classrooms: correlation between experimental data and mathematical models. *Building and Environment,* 44(4), 674-687.

de Dear, R. (2011). Revisiting an old hypothesis of human thermal perception: alliesthesia. *Building Research Information,* 39 (2), 108-117. doi: 10.1080/09613218.2011.552269.

de Dear, R. (2014). Thermal counterpoint in the phenomenology of architecture - A psychophysiological explanation of Heschong's "Thermal Delight". *Keynote speech, PLEA 2014,* 16 – 18 December 2014. Ahmedabad, India.

EN ISO 7730:2005. (2009). Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. ISO standard.

Galasiu, A. & Veitch, J.. (2006). Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Energy and Buildings,* 38(7), 728–742. http://doi.org/10.1016/j.enbuild.2006.03.001

Galatioto, A., Leone, L., Milone, D., Pitruzzella, S., & Franzitta, V. (2013). Indoor Environmental Quality Survey: A Brief Comparison between Different Post Occupancy Evaluation Methods, *Advanced Material Research*. 864–867, 1148–1152. doi:10.4028/www.scientific.net/AMR.864-867.1148.

Kim, J., de Dear, R., Candido, C., Zhang, H., & Arens, E. (2013). Gender differences in office occupant perception of indoor environmental quality (IEQ), *Building and Environment* 70, 245–256. doi:10.1016/j.buildenv.2013.08.022.

Leaman, A., & Bordass, B. (2001). Assessing building performance in use 4: The Probe occupant surveys and their implications, *Building Research Information* 29, 129–143. doi:10.1080/09613210010008045.

Li, P., Froese, T. M., & Brager, G. (2018). Post-occupancy evaluation: State-of-the-art analysis and state-of-the-practice review. *Building and Environment,* 133: 187–202.

Loonen, R. C., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews,* 25, 483-493.

Meir, I. A., Garb, Y., Jiao, D., & Cicelsky, A. (2009). Post-occupancy evaluation: An inevitable step toward sustainability. *Advances in building energy research,* 3(1), 189-219.

Pati, D., & Pati, S. (2013). Methodological issues in conducting post-occupancy evaluations to support design decisions, *Health Environments Research and Design Journal*. 6, 157–163. doi:10.1177/193758671300600312.

Preiser, W. (2005). Building Performance Assessment—From POE to BPE, A Personal Perspective*, Architectural Science Review*. 48 (2005) 201–204. doi:10.3763/asre.2005.4826.

Preiser, W. (1995). Post-occupancy evaluation: how to make buildings work better, Facilities. 13 (1995) 19–28.

Reinhart. CF, & Voss, K. (2003) Monitoring manual control of electric lighting and blinds. *Lighting Research Technology* 35(3):243-260.

Zagreus, L., Huizenga, C., Arens, E., & Lehrer, D. (2004). Listening to the occupants: a Web-based indoor environmental quality survey. *Indoor Air.* 14, 65–74. doi:10.1111/j.1600-0668.2004.00301.x.

Possibilities and Constraints for the Widespread Application of Solar Cooling Integrated Façades

Alejandro Prieto[1*], Ulrich Knaack[1], Tillmann Klein[1], Thomas Auer[2]

* Corresponding author
1 Delft University of Technology, Faculty of Architecture and the Built Environment, Department of Architectural Engineering + Technology, Architectural Façades & Products Research Group, The Netherlands, A.I.PrietoHoces@tudelft.nl
2 Technical University of Munich, Department of Architecture, Chair of Building Technology and Climate Responsive Design, Germany.

Abstract
Cooling demands in buildings have drastically increased in recent decades and this trend is set to continue into the near future, due to increasing standards of living and global climate change, among the most relevant factors. Besides energy consumption, the use of refrigerants in common vapour compression cooling technologies is a source of concern because of their environmental impact. Hence, there is a need to decrease cooling demands in buildings while looking for alternative clean technologies to take over the remaining loads. Solar cooling systems have gained increased attention in recent years, for their potential to lower indoor temperatures using renewable energy under environmentally friendly cooling processes. Nonetheless, their potential for building integration has not been fully explored, with the exception of scattered prototypes and concepts. This paper aims to address these knowledge gaps by presenting the results of the PhD research project 'COOLFAÇADE: Architectural integration of solar technologies in the building envelope'. The research project explored the possibilities and constraints for architectural integration of solar cooling strategies in façades, in order to support the design of climate responsive architectural products for office buildings, driven by renewable energy sources. This paper explores different aspects related to façade integration and solar cooling technologies, in order to provide a comprehensive understanding of current possibilities for façade integration, while drafting recommendations based on identified barriers and bottlenecks at different levels.

Keywords
solar cooling, integrated façades, façade design, renewables, barriers

DOI 10.7480/jfde.2018.3.2468

1 INTRODUCTION

Energy demands for cooling have increased drastically in recent decades, due to societal and economic factors such as higher standards of living and affordability of air conditioning, as well as environmental aspects such as temperature rise in cities in what is known as urban heat islands, and global climate change (Santamouris, 2016). Total energy projections for the coming decades show that energy consumption will keep rising, mostly driven by fast-growing emerging economies (BP, 2016; DOE/EIA, 2016), and cooling energy demands are expected to follow this trend (Jochem & Schade, 2009; OECD/IEA, 2015). As an example, yearly sales of room air conditioning units are expected to grow by 10-15%, going from 100 million worldwide in 2014, to an expected 1.6 billion by 2050 (Montagnino, 2017).

The first course of action in tackling this situation should always aim to reduce energy consumption through saving measures and the application of passive design strategies in buildings. Nonetheless, this is often not enough to avoid mechanical equipment altogether, particularly in the case of office buildings in warm climates, which are characterised by particularly high cooling demands (Qi, 2006). In this regard, solar cooling technologies have been increasingly explored, as an environmentally friendly alternative to harmful refrigerants used within vapour compression systems, while also being driven by solar - thus, renewable - energy. The principles behind some of these technologies have been researched for over a century, reaching mature solutions and components, and being recognised as promising alternatives to commonly-used air-conditioning units (Goetzler, Zogg, Young, & Johnson, 2014). Nonetheless, application in buildings remains mostly limited to demonstration projects and pilot experiences (Balaras et al., 2007; Henning & Döll, 2012).

Recently, façade integrated concepts have been explored as ways to promote widespread application throughout the development of multi-functional building components (Avesani, 2016; Ibañez-Puy, Martín-Gómez, Bermejo-Busto, Sacristán, & Ibañez-Puy, 2018; Prieto, Knaack, Auer, & Klein, 2017a; Xu & Van Dessel, 2008). However, while these are regarded as relevant and promising standalone concepts, further research is still needed to assess the integration potential of diverse solar cooling technologies, and identify any barriers that must be overcome, in order to promote the widespread application of solar cooling components in the built environment.

This paper aims to address these knowledge gaps by presenting the results of the PhD research project 'COOLFAÇADE: Architectural integration of solar technologies in the building envelope', carried out by the main author under the supervision of the co-authors. As the title suggests, the research project explored the possibilities and constraints for the architectural integration of solar cooling strategies in façades, in order to support the design of climate responsive architectural products for office buildings, without compromising the thermal comfort of users. The underlying hypothesis was that self-sufficient solar cooling integrated façades may be a promising alternative to conventional centralised air-conditioning systems widely used in office buildings in warm climates.

The research explored different aspects relating to façade integration and solar cooling technologies, in order to provide a comprehensive understanding of current possibilities for the development of architectural products. Hence, different types of barriers were identified, corresponding to distinct aspects that need to be considered in the development of integrated concepts. These specific findings have been presented separately and discussed in detail in previous publications. So, this article presents a collated summary of all results, focusing on the general discussion of overall possibilities after accounting for key aspects for further development, and drafting recommendations based on the identified constraints at different levels.

2 RESEARCH STRATEGY AND METHODS

The evaluation of the façade integration potential of solar cooling technologies was carried out considering two main families of parameters, targeting particular key aspects for the development and application of integrated façade concepts. Therefore, selected solar cooling technologies were assessed in terms of (a) architectural requirements for the integration of building services within the façade design and development process, and (b) the potential climate feasibility of self-sufficient integrated concepts, matching current technical possibilities with cooling requirements from several climates under an holistic approach to climate responsive façade design. The basic strategy behind the research project is summarised in Fig. 1.

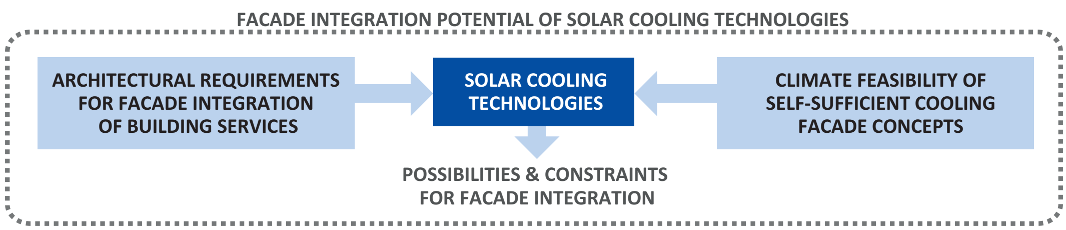


FIG. 1 Research strategy and parameters for the assessment

On the one hand, the response of the technologies to architectural requirements for façade integration was assessed qualitatively, based on a comprehensive review of the key aspects of each technology and their potential to overcome the main identified barriers for façade integration of building services. These barriers were previously identified and discussed by means of a survey addressed to experienced professionals in the fields of façade design and construction. The survey aimed to identify the main perceived problems relating to the façade integration of building services (Prieto, Klein, Knaack, & Auer, 2017), and the integration of solar collection technologies (photovoltaic panels and solar thermal collectors) (Prieto, Knaack, Auer, & Klein, 2017b), discussing specific barriers separately. The responses from the survey were interpreted using qualitative content analysis techniques and quantitative descriptive statistics, defining barriers relating to the design and construction process, as well as barriers relating to the products themselves.

On the other hand, the feasibility of applying integrated façade concepts in several climates was evaluated through numerical calculations based on climate data and building scenarios simulated with specialised software (EnergyPlus). The goal of this assessment was to check the theoretical feasibility of solar cooling façades as self-sufficient cooling units, matching solar availability at different orientations and locations, with the cooling requirements of a base scenario that consisted of a single office room in different climate contexts (Prieto, Knaack, Auer, & Klein, 2018). These scenarios considered several passive cooling strategies, such as shading, window-to-wall ratio, glazing type, and ventilation, as the first step of the assessment, obtaining optimised base scenarios for each orientation before integrating solar cooling technologies (Prieto, Knaack, Klein, & Auer, 2018).

The assessment focused on five main solar electric and solar thermal technologies, based on widespread categorisations: thermoelectric, absorption, adsorption, solid desiccant, and liquid desiccant cooling (Henning, 2007; Prieto, Knaack, et al., 2017a). Given that cooling needs are the main driver of the research, the assessment focused exclusively on warm climates, ranging from temperate to extreme desertic and tropical environments. Furthermore, discussion about design possibilities is constrained to the façade, leaving potential for further optimisation of cooling demands throughout building level strategies, which is outside the scope of the research project.

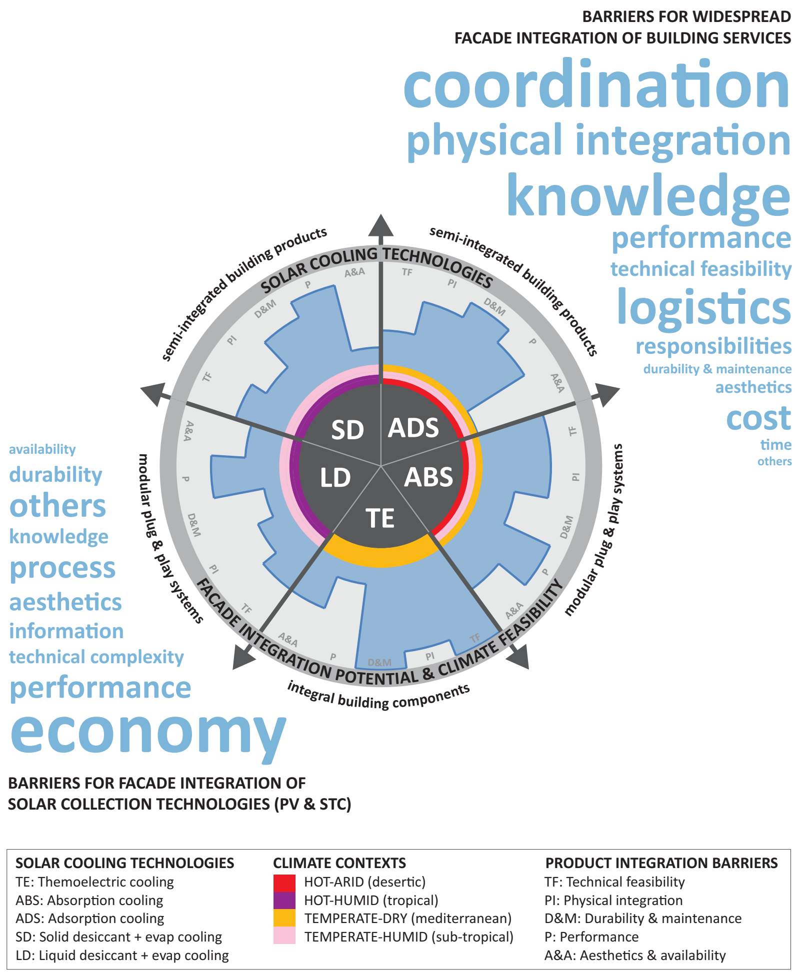


FIG. 2 Chart of current possibilities and identified barriers for the development of solar cooling integrated façades

3 RESULTS AND DISCUSSION

The driving force behind the research project was the intention to test the limits of solar cooling integration in façades, showcasing current possibilities while identifying technical constraints and barriers to be overcome to achieve a widespread application of integrated façade concepts. In response to this task, an overview of the main outcomes of the research project is presented in Fig. 2. This chart is regarded as a summarised panorama of the identified strengths and shortcomings of the assessed technologies in terms of façade integration; serving as a compass to guide further explorations and developments in the field.

The chart comprises several types of barriers acting at different levels, around a core composed of the solar cooling technologies assessed throughout the research project. The widespread application of integrated solar cooling façades will therefore depend on successfully overcoming each particular set of barriers. The ring around the core of solar cooling technologies consists of the threshold for façade integration of these systems, under self-sufficient operation in different climate contexts. Therefore, this ring shows distinct possibilities and constraints for each assessed technology, allowing them to be compared against each other. On the contrary, the barriers depicted outside of the circle are identified barriers for the development of solar cooling integrated concepts in general, applicable to all technologies; these consider barriers for further façade integration of solar collection technologies, namely photovoltaics and solar thermal collectors (lower left corner), and barriers for widespread façade integration of building services in general. The font size alludes to the perceived relevance of each barrier, based on how often it was mentioned by respondents of the survey (Prieto, Klein, et al., 2017). This comparative relevance only applies within each group of barriers separately, due to the nature of the assessment tool.

3.1 FAÇADE INTEGRATION POTENTIAL OF SOLAR COOLING TECHNOLOGIES

The potential for façade integration of each solar technology is represented by the shaded area around the inner core of solar technologies, summarising the qualitative evaluation conduced in terms of their ability to overcome product related key issues derived from the façade integration of building services. Technical feasibility, physical integration, durability & maintenance, performance, and aesthetics & availability were defined as these key issues, following analysis of the aforementioned expert survey conducted during the project.

First, it is clear that, although some technologies fare better than others, no technology currently meets all criteria in all required aspects for the development of self-sufficient integrated façade products, so further research and development is needed, targeting specific aspects. Table 1 shows the final recommendations for each technology in order to overcome current key barriers for façade integration. These were obtained from a qualitative evaluation that was presented in detail and discussed in a scientific article currently under review for publication (Prieto, Knaack, Auer, & Klein, n.d.). Recommendations that are marked in bold within particular aspects were identified as having particular shortcomings in relation to each technology, advocating for more pressing efforts on those matters.

Further developments and exploration focused on the generation of integrated building products, or plug & play compact systems, are needed for all assessed technologies. At the same time, the fact that liquid desiccant cooling technologies have only been explored recently, as opposed to other thermally-driven systems about which there is more knowledge, puts them at a disadvantage in both the level of development and technical maturity, needing further research in most aspects to be up to date. For adsorption and solid desiccant cooling, the main current bottlenecks are related to the size of components and the generation of compact integrated systems. This also holds true for some compact desiccant units currently being developed, which still need to be field tested and thoroughly validated under different working conditions (Finocchiaro, Beccali, Brano, & Gentile, 2016; SolarInvent, n.d.). Finally, thermoelectric modules are regarded as a promising technology for the development of integral building components, and absorption-based compact units present interesting prospects for modular plug & play systems for façade integration. Nevertheless, important performance barriers remain in the former, while further exploration of alternative working materials and testing of compact modular units are the main challenges for the latter.

KEY PRODUCT RELATED ISSUES FOR FAÇADE INTEGRATION	THERMOELECTRIC COOLING	ABSORPTION COOLING	ADSORPTION COOLING	SOLID DESICCANT COOLING	LIQUID DESICCANT COOLING
Technical feasibility	Prototype testing and experimental measurement of façade integrated concepts.	Further exploration and development of compact systems for façade integration.	**Size reduction of components and exploration of alternative processes.**	**Development and validation of compact systems for façade integration.**	**Development and testing of compact units.**
Physical integration	Standardize connections and components for development of architectural products.	Further exploration of plug & play integrated approaches to system design.	Exploration of integrated systems.	**Exploration of integrated compact systems.**	**Exploration of alternative processes to simplify connections and increase compatibility.**
Durability & maintenance	Testing of durability of TE modules applied in building components over time and different climate conditions.	**Exploration of non-corrosive working pairs and vacuum sealed compact systems.**	Testing of compact adsorption systems over time and different climate conditions.	Testing of compact solid desiccant systems over time and different climate conditions.	**Exploration and testing of alternative non-corrosive materials.**
Performance	**Increase cooling power of peltier modules, balancing adequate COP values. Explore up-scaled components.**	Further development and testing of compact systems below 3kW.	Increase COP values of small scale systems.	Further development and testing of compact systems below 3kW for reliability of COP values.	Further development and testing of compact systems below 3kW for reliability of COP values.
Aesthetics & availability	**Development of architectural products and integrated building components.**	**Development of plug & play systems for façade integration.**	**Size reduction of components for development of plug & play systems.**	**Size reduction and simplification of connections for development of decentralised ventilation systems.**	**Development and validation of compact integrated systems for future product development.**

TABLE 1 Recommendations for further development of solar cooling technologies for façade integration purposes

3.2 THEORETICAL CLIMATE FEASIBILITY OF SELF-SUFFICIENT SOLAR COOLING FAÇADES

The inner ring shows the climate contexts where self-sufficient application could be theoretically feasible, based on the development of integrated concepts based on specific technologies. Results from numerical calculations showed that the application of these concepts could be feasible on virtually all orientations, from every assessed location (Prieto et al., 2018). Even though these outcomes followed a theoretical approach, based on several assumptions and referential values, this fact is regarded as evidence that the application of self-sufficient solar cooling façades is not a far-fetched concept and could indeed be promoted following further technical developments to overcome previously identified barriers for façade integration. Nevertheless, the self-sufficiency of these concepts is conditioned by important restrictions for façade design in most cases, seeking to optimise the solar input throughout lower panel tilt and bigger dimensions of photovoltaic/thermal collector solar arrays in the building façade. These design constraints are more persistent in south and north façades, making east and west orientations more generally suited to solar cooling applications.

With regard to the climatic application potential of the assessed technologies, there are clear research and development paths. Although solar electric processes present advantages for façade integration, as previously discussed, their overall performance is a significant barrier, allowing for application in mild temperate dry climates, as a best case scenario, under medium to strong design constraints. Solar thermal offers more possibilities, further research is recommended for the application of sorption-based concepts in temperate and hot-arid contexts with minor to medium constraints, depending on orientation and climate severity. Finally, desiccant based units are recommended for warm-humid environments, both due to higher efficiencies associated with the technology, and particular general suitability to handle larger latent loads. In Hong Kong and Singapore, west, east, and north applications are theoretically feasible with medium design constraints, but south applications are heavily hindered.

The design constraints discussed refer to requirements for the optimisation of the solar array. However, basic design constraints remain for the application of all concepts, based on the collection technology needed to achieve the reference efficiencies used in the calculations. Presently, building integrated solar thermal (BIST) and photovoltaic (BIPV) products such as coloured thermal collectors or transparent PV cells, especially designed to appeal to architects, have lower efficiencies than state-of-the-art basic systems with no 'aesthetical considerations'. Hence, further development of these technologies is needed to expand the general range of façade design possibilities. Furthermore, the self-sufficiency of integrated concepts is conditioned to the use of passive strategies to lower cooling demands to a manageable amount. If these concepts are theoretically possible under important design constraints, their feasibility is downright impossible without being embedded within a climate responsive approach to façade design.

3.3 GENERAL BARRIERS FOR FAÇADE INTEGRATION OF BUILDING SERVICES AND SOLAR COLLECTION TECHNOLOGIES

In general, barriers related to the overall process are perceived as more critical issues to solve than issues relating to the end product itself, to allow for widespread façade integration of building services. In particular, problems related to coordination of different professional areas are perceived to be the most relevant, which holds true in all three defined stages of façade development (design, production, and assembly). In terms of other frequently mentioned process related problems, lack of technical knowledge seems to be especially relevant during design and assembly stages, and less so during production. Nonetheless, several logistical issues were identified in production and assembly stages, focusing on the lack of flexibility within the production chain, together with economic barriers during production for the construction of high quality components, aggravated by a common underestimation of cost projections during design phases. Finally, other mentioned problems, which are minor in comparison, refer to undefined responsibilities and warranties throughout the overall process.

In terms of product related problems, the physical integration of components seems to be the most relevant issue during both production and assembly stages. Additionally, the inaccuracy of long term performance estimations and operational limitations of currently available systems were stated as relevant problems in the design stage. Furthermore, other product related barriers that were identified, albeit with fewer mentions across all stages, are: the technical feasibility of integrated concepts; durability and maintenance; and aesthetics and lack of variety of available building services for integration. Even though these problems do not seem to hold the same importance as process related aspects, they represent basic requirements and relevant challenges that must be overcome on the development path of components and systems for façade integration.

Regarding the particular integration of solar collection technologies in façades, economic issues were declared as the most pressing barrier to overcome. The cost of current systems, energy prices, and the lack of economic incentives were mentioned among key aspects within this barrier. Secondly, grouped product related issues were perceived as a highly relevant barrier, based on the total amount of mentions. The disaggregated exploration of product related issues refers to performance, technical complexity of the systems, aesthetics, durability, and product availability. Besides performance, aesthetics is a relevant perceived issue to be overcome, which makes sense considering the strong impact of solar collectors and PV panels on the external finish of the façade and thus, the outward appearance of buildings.

4 CONCLUSIONS

General results based on the assessment of current possibilities show that self-sufficient integrated façade concepts based on solar cooling technologies are still far from achieving widespread application. However, there is clear potential for further development of distinct integrated concepts, based on specific technologies, provided that we manage to overcome existing barriers and technical bottlenecks. The main recommendations for further research and development in the field follow the different types of barriers discussed in the paper, posing specific challenges for diverse disciplines.

First, there is a need for further research on small-scale solar cooling systems and components, aiming to increase current efficiencies and simplify their operation. Fundamental research on new working materials and alternative cooling processes derived from the main addressed principles would enhance the potential for application at a base technological level. Furthermore, experimental and applied research at a system level is encouraged for all cooling technologies, in order to develop integrated building components, or modular compact plug & play units for façade integration purposes. Fundamental research needs to be carried out by specialists, but the development of systems conceived for architectural integration would greatly benefit from a multidisciplinary approach, in order to tackle technology-specific challenges.

Similarly, the integration of solar collection technologies in façades needs to be further promoted. The technical optimisation of these systems is currently well on track, steadily achieving performance goals set by different technological roadmaps, whilst there is an increasing number of products conceived with 'aesthetical considerations' in mind. Nonetheless, important economic restrictions remain in order to promote widespread application. Recommended actions to mitigate this include the further manufacturing of cost-effective products for integration by system developers, technical improvements in electricity and heat storage technologies, and the exploration of new business models and subsidy schemes to incentivise their application.

Finally, further parallel actions are needed to push for the integration of building services and new technologies for high-performing façades in general. Building technologies should be a central part of façade design education, striving for a basic understanding of technical aspects of building systems and façade requirements under an integrated design approach. Moreover, the façade manufacturing industry should take the lead in the exploration of new production processes, simplifying logistical and coordination issues derived from the integration of several systems, under an integrated supply chain. Furthermore, research on innovative business models for the management of façade systems could change the current value chain, generating new incentives for the development and application of high-performing façades under an environmentally conscious design approach.

Acknowledgements
This paper is part of the ongoing PhD research project titled COOLFAÇADE: Architectural Integration of Solar Cooling Technologies in the Building Envelope, developed within the Architectural Façades & Products Research Group (AF&P) of the Department of Architectural Engineering + Technology, Delft University of Technology (TU Delft). The research project is being funded through a scholarship granted by CONICYT, the National Commission for Scientific and Technological Research of Chile (Resolution N°7484/2013).

References

Avesani, S. (2016). *Design of a solar façade solution with an integrated sorption collector for the systemic retrofit of the existing office buildings*. (Doctoral thesis). Leopold-Franzens-Universität Innsbruck, Innsbruck, Austria.

Balaras, C. A., Grossman, G., Henning, H.-M., Infante Ferreira, C. A., Podesser, E., Wang, L., & Wiemken, E. (2007). Solar air conditioning in Europe—an overview. *Renewable and Sustainable Energy Reviews,* 11(2), 299-314. doi: 10.1016/j.rser.2005.02.003

BP (2016). *BP Energy Outlook, 2016 edition*. London, United Kingdom.

DOE/EIA (2016). *International Energy Outlook 2016.* Washington D.C., USA: US Energy Information Administration, US Department of Energy.

Finocchiaro, P., Beccali, M., Brano, V. L., & Gentile, V. (2016). Monitoring Results and Energy Performances Evaluation of Freescoo Solar DEC Systems. *Energy Procedia,* 91, 752-758. doi: 10.1016/j.egypro.2016.06.240

Goetzler, W., Zogg, R., Young, J., & Johnson, C. (2014). *Energy savings potential and RD&D opportunities for non-vapor-compression HVAC technologies*. USA: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office.

Henning, H.-M. (2007). Solar assisted air conditioning of buildings – an overview. *Applied Thermal Engineering,* 27(10), 1734-1749. doi: http://dx.doi.org/10.1016/j.applthermaleng.2006.07.021

Henning, H.-M., & Döll, J. (2012). Solar Systems for Heating and Cooling of Buildings. *Energy Procedia,* 30, 633-653. doi: 10.1016/j.egypro.2012.11.073

Ibañez-Puy, M., Martín-Gómez, C., Bermejo-Busto, J., Sacristán, J. A., & Ibañez-Puy, E. (2018). Ventilated Active Thermoelectric Envelope (VATE): Analysis of its energy performance when integrated in a building. *Energy and Buildings*, 158, 1586-1592. doi: 10.1016/j.enbuild.2017.11.037

Jochem, E., & Schade, W. (2009). 2-degree scenario for Europe - policies and impacts. *ADAM: Adaptation and mitigation strategies: supporting European climate policy.* Karlsruhe: Fraunhofer Institute for Systems and Innovation Research (Fraunhofer-ISI).

Montagnino, F. M. (2017). Solar cooling technologies. Design, application and performance of existing projects. *Solar Energy*. doi: 10.1016/j.solener.2017.01.033

OECD/IEA. (2015). *Energy and climate change / World Energy Outlook Special Report*. Paris, France: IEA - International Energy Agency.

Prieto, A., Klein, T., Knaack, U., & Auer, T. (2017). Main perceived barriers for the development of building service integrated façades: Results from an exploratory expert survey. *Journal of Building Engineering,* 13, 96-106. doi: 10.1016/j.jobe.2017.07.008

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2017a). SOLAR COOLFAÇADES Framework for the integration of solar cooling technologies in the building envelope*. Energy,* 137, 353-368. doi: 10.1016/j.energy.2017.04.141.

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2017b). Solar façades – Main barriers for widespread façade integration of solar technologies. *Journal of Façade Design and Engineering*, 5(1), 51-62. doi: 10.7480/jfde.2017.1.1398

Prieto, A., Knaack, U., Auer, T., & Klein, T. (2018). Feasibility Study of Self-Sufficient Solar Cooling Façade Applications in Different Warm Regions. *Energies*, 11(6), 1475. doi: 10.3390/en11061475

Prieto, A., Knaack, U., Klein, T., & Auer, T. (2018). Passive cooling & climate responsive façade design - Exploring the limits of passive cooling strategies to improve the performance of commercial buildings in warm climates. *Energy and Buildings, 175, 30-47. doi: 10.1016/j.enbuild.2018.06.016.*

Prieto, A., Knaack, U., Auer, T., & Klein, T. (n.d.). COOLFACADE: State-of-the-art review and evaluation of solar cooling technologies on their potential for façade integration. *Renewable & Sustainable Energy Reviews*, (under review).

Qi, C. (2006). *Office Building Energy Saving Potential in Singapore*. (Master's Thesis). National University of Singapore (NUS), Singapore.

Santamouris, M. (2016). Cooling the buildings – past, present and future. *Energy and Buildings,* 128, 617-638. doi: 10.1016/j.enbuild.2016.07.034

SolarInvent. (n.d.). *Freescoo / SolarInvent S.r.l.* - http://www.freescoo.com. (accessed on April 11th 2018).

Xu, X., & Van Dessel, S. (2008). Evaluation of an Active Building Envelope window-system. *Building and Environment,* 43(11), 1785-1791. doi: 10.1016/j.buildenv.2007.10.013

Smart and Multifunctional Materials and their Possible Application in Façade Systems

Miren Juaristi[1*], Aurora Monge-Barrio[1], Ulrich Knaack[2], Tomas Gómez-Acebo[3]

* Corresponding author
1 Universidad de Navarra, School of Architecture, Spain, mjuaristi@alumni.unav.es
2 Faculty of Architecture and The Built Environment, TU Delft, The Netherlands
3 Universidad de Navarra, TECNUN School of Engineers, Spain

Abstract

Today's society needs to face challenging targets relating to environment and energy efficiency, and therefore the development of efficient façade systems is essential. Innovative concepts such as Adaptive Building Façades might play a role in the near future, as their dynamic behaviour could optimise the performance of a building. For their successful development, a balance between sophistication and benefit is necessary and the implementation of Smart and Multifunctional Materials in building envelopes could be the key, as they have the ability to repeatedly and reversibly change some of their functions, features, or behaviours over time in response to environmental conditions. However, these materials were predominantly developed for use in other fields, and there is a lack of specific technical information to evaluate their usefulness in façade engineering. The aim of this paper is to collect the critical information about promising responsive materials for use in the design of Adaptive Façades, in order to help designers and technicians in decision-making processes and to scope possible future applications in façades. Investigated materials were analysed from the Building Science standpoint; their weaknesses and threats in the built environment were highlighted, and their technical feasibility was examined through the study of their availability in the current market.

Keywords

responsive, autoreactive, intelligent, adaptive, design, innovation

DOI 10.7480/jfde.2018.3.2475

1 INTRODUCTION

Architecture and façade engineering are usually considered to be "conservative" fields in relation to the application of innovative materials. The complexity of requirements that they have to meet, as well as their interdisciplinary nature, make it difficult to achieve paradigm changes. However, new challenges, such as NZEB targets and low-carbon-based economies, put pressure on the development of new design approaches and strategies. Thus, the implementation of Smart and Multifunctional Materials might be more achievable than it may have seemed some years ago. These materials can respond reversibly and intelligently to changes in the surrounding environment without any external actuators, and this could be useful when designing adaptive, responsive, or intelligent façades, as the robustness of complex mechanisms is a critical issue (Loonen, Trčka, Cóstola, & Hensen, 2013).

Broadly speaking, the best known responsive materials are Smart Materials, highly engineered materials that can modify their function or behaviour (Addington & Schodek, 2005). Addington and Schodek (2005) distinguish two types of materials according to the way they react. Type 1 materials change in one or more properties in direct response to a variation in the surrounding environment. Some of these materials are already being applied in building technology, such as electrochromic windows (Addington & Schodek, 2005; Gavrilyuk, Tritthart, & Gey, 2007; Granqvist, 2014), which change their surface emissivity when there is a change in the voltage field (see Section 3). On the other hand, Type 2 materials react by transforming one energy form to an output energy in another form. For instance, electroactive materials transform electrical energy into mechanical energy and vice versa (Madden, 2008).

Additionally, some new composite materials also present multifunctional properties, as they were designed to have a desired multiple response, and are referred to as Multifunctional Materials (MM) in this paper. At this point, it is important to note that multi-ability, or multi-function, has a different denotation than the concept of adaptability, as different objectives can be fulfilled consecutively and not only concurrently (Loonen et al., 2013). Thus, MMs are non-homogenous materials in shape and/or composition, and if their anisotropy is properly controlled, they behave differently according to the external conditions (Reichert, Menges, & Correa, 2015). For example, thermobimetals comprise two sheets of differing metals alloys which, as they are laminated together, expand at different rates causing the bending of the component as a response to a temperature gradient (Adriaenssens et al., 2014; López, Rubio, Martín, Croxford, & Jackson, 2015). This bending could create various desired but not concurrent façade morphologies, and the different geometries might enhance the performance of a façade component. For instance, the cladding of a ventilated façade could be as closed as possible in the insulation mode (function 1) or have an open-joint configuration in the heating-dissipation mode (function 2) (Juaristi, Monge-Barrio, Sánchez-Ostiz, & Gómez-Acebo, 2018). Furthermore, in recent years, the development of complex software and innovative manufacturing processes allow for greater control of the structural composition of the materials, which make possible the design of multi-functional and multi-property elements. These materials, designed by computational techniques, are also known as Information Materials (Kretzer, 2017) but their possible application in façade technologies is still unclear and they were not addressed in this paper.

The general consensus about multi-functional or adaptive materials is that they are often too sophisticated and therefore expensive (Kretzer & Hovestadt, 2014), and that even so, their service life is too short. However, there is a lack of technical information to establish this assumption as true for each SM or MM. This paper studies not only the common characteristics of a material family, but goes further in the analysis of specific materials. It enables the detection of potential materials for the building industry and the determination of whether they would perform properly in façade applications. To foresee this possibility, first the possible roles of a material in a dynamic façade element were proposed and their design potential and limitation analysed (Section 3). Secondly, different properties predetermining the dynamic performance of the material were explained (Section 4) and, to conclude, the importance of knowing specific physical properties of these materials was highlighted and further areas of research were suggested (Section 5).

2 METHODOLOGY

This paper collected technical information about Smart and Multifunctional Materials applied not only in the façade industry but in any field, as long as their operational scenarios and scales of adaptability matched with façade requirements. The criterion for the inclusion of adaptive materials in this review was the operational scenario, the fatigue life, and their scale of adaptability (defined in Section 4), according to their possible roles (Section 3). For instance, thermochromic materials with potential uses in external claddings were only included when they perform at ambient temperature and when their fatigue life is longer than the service life of the façade element. When considering materials with kinetic responses to be applied in movable double skins, only materials with reactions of a magnitude of centimetres were considered.

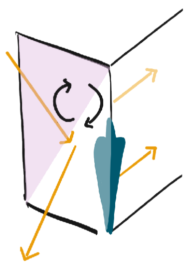
The results shown in this paper were obtained from scientific papers, Open Access Material Databases (materia,n.d.-a; Materiability, n.d.-a) and from market products information (Dynalloy, Inc., n.d.; Fraunhofer Institute for Applied Polymer Research IAP, n.d.; Kanthal, n.d.; LCRHallcrest, n.d.; QCR Solutions Corp, n.d.; Smart Films International, n.d.). Scientific papers were particularly interesting for identifying different adaptive materials and understanding their dynamic operation. However, when scoping possible innovative roles, online multidisciplinary databases and market available products were especially valuable as their information helped to analyse design potential and limitations.

3 POSSIBLE APPLICATION OF SM/MM IN ADAPTIVE FAÇADE ELEMENTS

3.1 SMART WINDOWS

The application of SM/MM in smart windows provide two types of dynamic performance: shading and climate control (Fig. 1). Those Smart Materials used for a shading reaction are the most developed and are mainly available in the market as part of window components (Addington & Schodek, 2005; Granqvist, 2014; Lampert, 2003; Mlyuka, Niklasson, & Granqvist, 2009). At the present time, these materials can be implemented as thin films (Gavrilyuk et al., 2007; Granqvist, 2014; Mlyuka et al., 2009; Seeboth, Ruhmann, & Mühling, 2010; Smart Films International, n.d.), directly in the glass using nanotechnology in the chemical composition (Granqvist, 2014; materia, n.d.-b; Seeboth et al., 2010) or as inks, pigments or dyes (QCR Solutions Corp, n.d.; Seeboth et al., 2010).

The main families of technologies that provide a shifting surface colour are electrochromics, thermochromics, and photochromics, and their differentiation factor is the input by which their response is activated. Electrochromics react to a change in the voltage field (Gavrilyuk et al., 2007; Granqvist, 2014); thermochromics change their colour at a set temperature (Kretzer, 2017; Ma & Zhu, 2009); and photochromics change when they are exposed to UV radiation (Zhang, Lee, Mascarenhas, & Deb, 2008). Similarly, in thermotropics, the change of the light scattering properties at certain operational temperatures is caused by a phase separation process at molecular level (Seeboth et al., 2010).



Possible Component	Role	Material Family	Autorreactive facade element	Color
Smart Window	Self Shading	Electrochromics	A. film B. special chemical composition/ nanotechnology	BL / transparent W GR GR / transparent
		Thermochromic	A. film B. ink/pigments C. Dyes	BL BL GN BR GR PU / transparent R O PI GN B / transparent OC / transparent
		Photochromic	A. film	BL BL Y R GN GN O BR PU PI PI / transparent
		Thermotropic	A. film B. special chemical composition/ nanotechnology	GR BR BL Y GR BR GN BL B / transparent
	Heating effect	Thermoelectrical	A. film	transparent

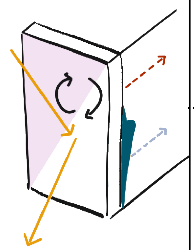
Legend

W White	BL BL Blue	BR BR Brown	O Orange	GN GN GN Green	PU Purple
B Black	GR GR Grey	OC Ochre	Y Yellow	PI PI Pink	R Red

FIG. 1 Responsive materials that could be used in smart window components and meaningful design features.

3.2 OPAQUE ADAPTIVE FAÇADE COMPONENTS

Even if the application of responsive materials in opaque façade components is less developed than in transparent façade components, there is a wide range of possible roles for which they could be used. Firstly, they could be used in exterior claddings to modify the surface temperature to optimally control the thermal performance of the outer skin (Ma & Zhu, 2009). Experimental assessments were made for materials that change their colour at a specific temperature (thermochromics), but as electrochromics or photochromics modify their solar heat radiation factor, this effect might also modify the surface temperature of façades, and therefore, their thermal performance. All of these materials are Smart Materials, which means that the available colour range depends on their chemical composition, and as there are, as yet, few chemical structures providing this responsive performance, there are few colour options for each material family (Fig. 2). Besides, most of the time these colours are vivid, which could be a challenge when applying them in some urban contexts. Anyway, to really evaluate the application of these materials in responsive façade elements, the holistic behaviour of the system needs to be considered, as it is illogical to try to collect solar thermal energy throughout the cladding if the envelope completely blocks thermal flux.

Possible Component	Role	Material Family	Autorreactive facade element	Color
 Exterior cladding	Temperature change (color switch)	Thermochromic	A. film B. ink/pigments C. Powder D. Plastic pellets E. Dyes	BL BL GN BR GR PU / transparent R O PI GN B / transparent OC / transparent
	Solar reflectance change (opacity switch)	Electrochromic	A. film	BL / transparent
		Photochromic	A. film	BL BL Y R GN GN O BR PU PI PI / transparent

Legend

W White	BL BL Blue	BR BR Brown	O Orange	GN GN GN Green	PU Purple
B Black	GR GR Grey	OC Ochre	Y Yellow	PI PI Pink	R Red

FIG. 2 Responsive materials that could be used in opaque exterior claddings and meaningful design features.

To tackle this problem, components made by SM or MM could be applied in the intermediate façade layer as embedded devices that control heat flow (Fig. 3). Phase change materials are good examples of responsive thermal control materials and, while they are no longer widely used in the building environment, the current scientific research is quite advanced and shows that they have high potential for reducing heating and cooling energy demand (Cabeza, Castell, Barreneche, De Gracia, & Fernández, 2011).

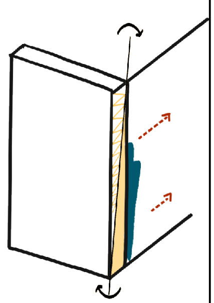
Possible Component	Role	Material Family	Autorreactive facade element	Color
 Intermediate Layer	Integrated thermal control	Thermoelectrical	A. device	irrelevant
		Phase Change Materials	A. intermediate layer B. device	W / transparent

FIG. 3 Responsive materials that could be used in intermediate layers and meaningful design features.

Lastly, interior cladding could also have an adaptive reaction that would be useful in controlling the hygrothermal conditions of the interior environment (Fig. 4). Materials that have high humidity absorption, such as natural porous materials or hydrogels, could be used not only to achieve a suitable level of humidity in the air, but also to cause an evaporative cooling effect (Markopoulou, 2015). This behaviour could be integrated directly in the material used in the interior surface (Maeda & Ishida, 2009; Watanabe, Fukumizu, & Ishida, 2008) or as devices (Raviv et al., 2014).

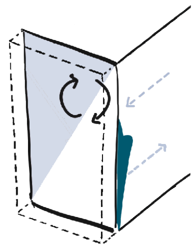
Possible Component	Role	Material Family	Autorreactive facade element	Color
 Interior cladding	Integrated hygrothermal control	Hydrothermally solidified soil bodies	A. Interior surface	BR GR W / customized
		Natural porous materials		They can be coated / painted
		Hydrogels	A. device B. surface	W / transparent

FIG. 4 Responsive materials that could be used in opaque interior claddings and meaningful design features.

3.3 MOVABLE OR KINETIC SKINS

Reactive materials with a kinetic or shape-changing ability might also have a broad field of application in movable skin façades (Fig. 5). The most developed role is shading, as these materials modify their dimension when an external stimulus exists, such as temperature rise or solar radiation incidence. They could trigger the motion of the outer skin when they are incorporated in the external surface (Adriaenssens et al., 2014; Fiorito et al., 2016), when they are placed at joints, or as external actuators in flexible components. There are already some built examples (Laughlin & Howes, 2012), however, mechanical actuators are more widely used than those that are embedded in materials (Loonen et al., 2013).

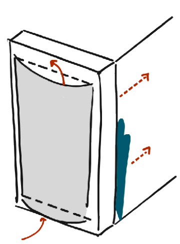
Possible Component	Role	Material Family	Autorreactive facade element	Material´s finish
 Movable double skin	(1) Enhance / block thermal dissipation (2) Auto-reactive air dampers (3) Automatic shading devices	Electroactive polymers	A. surface B. actuator	transparent
		Thermobimetals	A. surface B. actuator C. joint	metal
		Shape Memory Alloy		
		Heat sensitive plastics		miscellaneous
		Light responsive polymer		
		Shape Memory Polymers		
		Shape memory Hybrids		
	(1) Enhance / block thermal dissipation (2) Auto-reactive air dampers	Natural Hygromorphs	A. surface B. actuator C. joint	wooden
		Hygromorph bi-layer composites		
		Hygromorph Bio-composites		-
		Synthetic Composites	A. actuator B. joint	-
		Hydrogels		white/ transparent gel
	Auto-reactive air dampers	CO2 Responsive Polymers	A. actuator B. joint	-

FIG. 5 Responsive materials that could be used in movable double skins and meaningful design features.

Furthermore, materials that modify their dimensions in reaction to different inputs could be used to provide automatic ventilation, as was demonstrated in a functional prototype which responded to humidity (Reichert et al., 2015). Although several materials with a kinetic response were found in the literature review, such as CO2 responsive polymers (Lin & Theato, 2013), hydrogel actuators (Markopoulou, 2015), or materials responding to temperature changes (Adriaenssens et al., 2014; Fiorito et al., 2016; López et al., 2015), their possible façade performance was not explored. Even so, their potential to provide automatic ventilation according to these environmental inputs looks promising. The main drawback of these possible new roles is that if responses were self-induced, it would make it impossible to override adaptation in contrast with the electrical input. For that reason, climate and use conditions should be considered with an overall perspective to determine if the construction of auto-reactive air dampers would be suitable for energy and comfort requirements.

Lastly, these kinds of materials could also enhance the thermal behaviour of ventilated opaque façades (Juaristi et al., 2018). They could open or close the air cavity between the outer and inner skin depending on the exterior temperatures and wind conditions. The convective movements occurring in the cavity could be enhanced or blocked to control thermal dissipation.

3.4 DESIGN POTENTIAL AND LIMITATIONS

One of the most challenging tasks when trying to face the dissemination gap between different scientific fields and façade engineering was to learn *how* these materials look. Each sector has its application scale, roles, and restrictions, and usually, SMs and MMs are manufactured in such a way that they are not adequate for the built environment, making it even harder to envision their potential new uses. In order to boost the implementation of innovative materials in façades, technology applicators need to understand the determining factors of each material and the detection of the following design parameters is essential:

- Available colours (Fig. 1 - Fig. 5)
- Possible geometries due to material family and type of façade elements (Fig. 1 - Fig. 5)
- Thickness
- Width
- Length
- Assembly method
- Manufacture process

Such information was found for electrochromics (Granqvist, 2014; Smart Films International, n.d.), thermochromics (materia, n.d.-b; Materiability,n.d.-b; Mlyuka et al., 2009; QCR Solutions Corp, n.d.; Smart Films International, n.d.), photochromics (LCRHallcrest, n.d.; Reichert et al., 2015), thermotropics (Seeboth et al., 2010), shape memory alloys (Dynalloy, Inc.; Fiorito et al., 2016; Madden, 2008), electroactive polymers (Fiorito et al., 2016; Jiang, Kelch, & Lendlein, 2006; Madden, 2008; Markopoulou, 2015; Samatham, Kim, & Dogruer, 2007) and hydrogels (Materiability, n.d.-c), as they are currently commercialised products and manufacturers provide useful information for design considerations. Besides, materials belonging to the same product family usually have some similar characteristics, especially regarding the possible geometries. For instance, thermochromics and electrochromics come mainly as rectangular rolls and sheets (materia, n.d.-b; Smart Films International, n.d.), whereas self-shaping materials are most often manufactured as strips (Dynalloy, Inc., n.d.; Kanthal, n.d.; Materiability, n.d.-d; Fiorito et al., 2016; Jiang et al., 2006), wires (Dynalloy, Inc., n.d.; Fiorito et al., 2016), beams (Adriaenssens et al., 2014) and sheets (Fiorito et al., 2016; Samatham et al., 2007).

Little information was found in relation to assembly methods and manufacture process, and more research should be undertaken to get this information, which would be necessary in order to foresee more design options beyond those commercially available.

4 DYNAMIC OPERATION AND ADAPTIVE MATERIALS

When classifying Smart and Multifunctional Materials in families, the common feature is the dynamic operation that they are able to provide (Addington & Schodek, 2005). Accordingly, in this section, we detected and grouped specific materials and studied the relevant properties that enable an understanding of their adaptive performance. Based on the parameters that Loonen et al. established as key factors for climate responsive façade elements, it is essential to find accurate information about the mechanism of actuation of each material, the range and velocity of adaptation, the type of control, the operational scenario and their fatigue life (Loonen et al., 2013).

4.1 CONTROL OF VISIBLE LIGHT AND SOLAR TRANSMITTANCE. REVERSIBLE COLOUR CHANGE

Responsive materials can enhance thermal performance and/or daylight by switching visible transmittance and/or solar heat gain coefficient. Nowadays, there are several electrochromic, thermochromic, photochromic, and thermotropic products available on the market, mainly for smart windows. Fig. 6 shows visible transmittance and solar transmittance range for some of these products. Colour is of great importance, as the lighter it is, the more daylight is provided and the less solar transmittance is blocked. If the purpose of the material is to boost indoor natural light, the use of some of these electrochromic products is questionable, as their highest value doesn't reach 40% visible light transmission. Indeed, if the aim is to control thermal performance, then solar transmittance is the key parameter to look at in this graph.

Furthermore, when applying electrochromic materials, a balance should exist between the required electrical current and the obtained energy saving; oxide films look like a promising solution to meet this purpose (Fig. 7). Finally, some commercialised thermochromics (QCR Solutions Corp, n.d.; Smart Films International, n.d.) and photochromics (LCRHallcrest, n.d.) that are available on the market don't have a suitable life-span for façade engineering, as UV degrades them quickly. The reason why this does not happen in switchable windows may be due to the fact that the glass blocks the majority of UV radiation, which could extend the service life of the component.

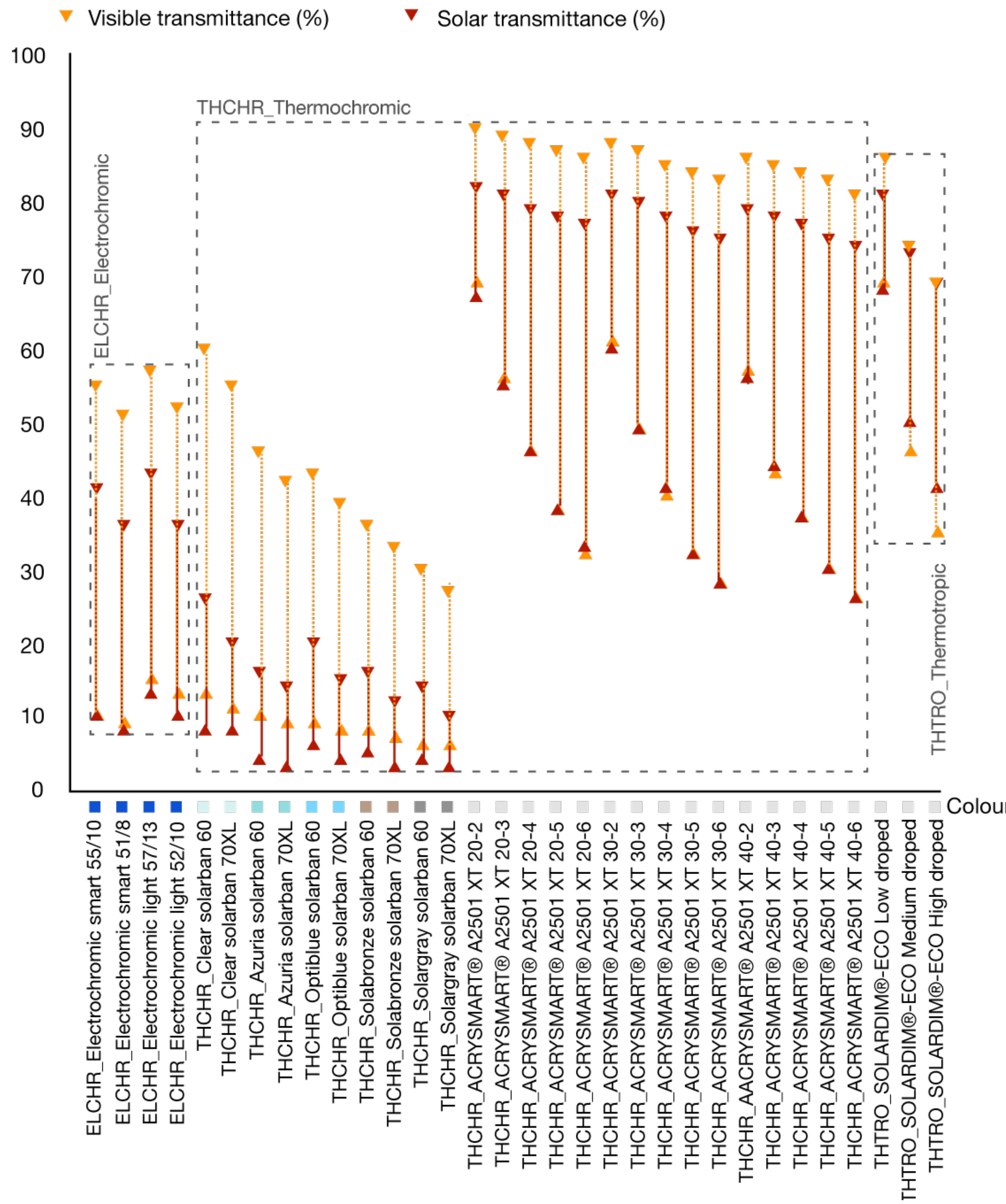


FIG. 6 Visible transmittance and solar transmittance of some electrochromic, thermochromic, and thermotropic products available on the market

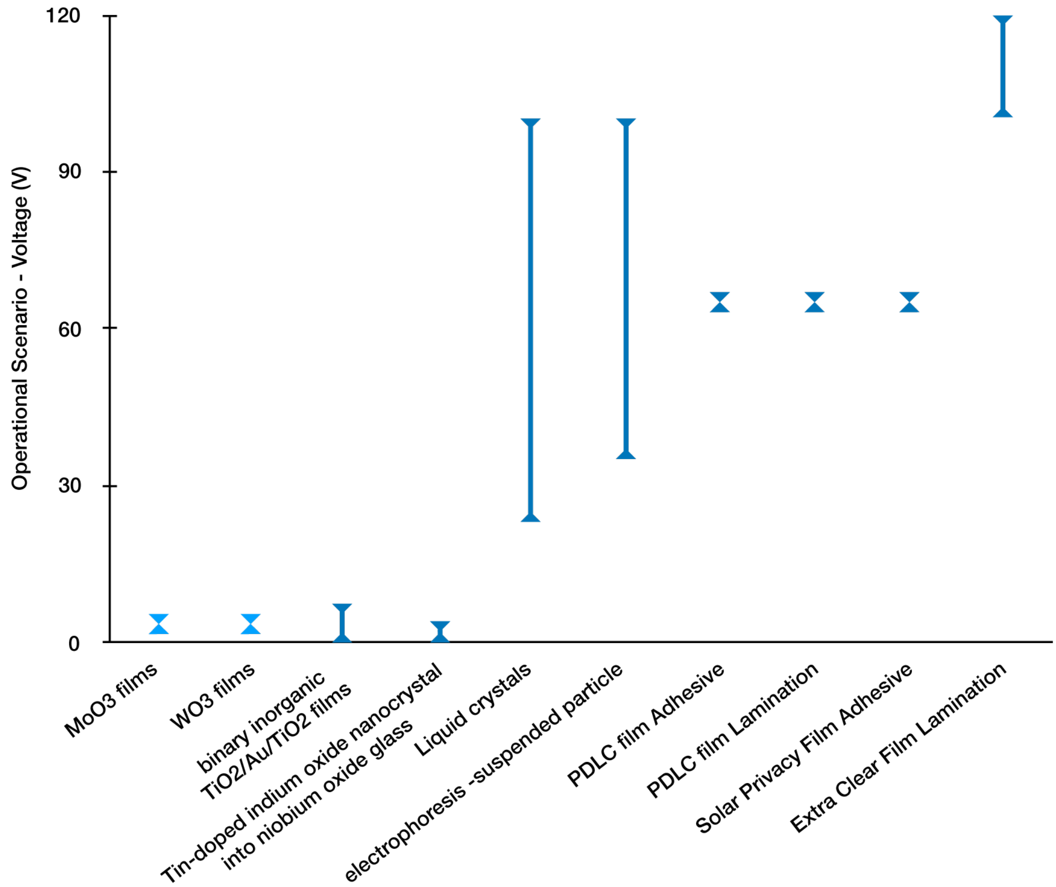


FIG. 7 Required voltage to activate some meaningful electrochromic materials

4.2 REVERSIBLE HEAT FLOW DIRECTION

Thermoelectrical materials, such as Bi2Te3 based compositions, create a hot and cold junction when an electrical input is applied and a temperature difference occurs between the two faces of the material as a result. If these materials were applied in façades, the direction of thermal flux could be controlled to obtain the desired effect (the enhancement of energy exchange or the insulation) (Addington & Schodek, 2005; Ibañez-Puy, Bermejo-Busto, Martín-Gómez, Vidaurre-Arbizu, & Sacristán-Fernández, 2017).

4.3 ELECTRICALLY ACTIVATED MECHANICAL DISPLACEMENT (AND THE CONVERSE)

Electroactive materials, also known as piezoelectric materials, can produce a mechanical displacement when an electrical current is applied and conversely, the material can produce an electrical signal when a mechanical displacement occurs, as molecular structures are electrically polarised when a stress force is applied to the material (Kornbluh, 2008; Madden, 2008; Samatham et al., 2007). This could be applied in kinetic façade components, and there are already some built examples, such as the ShapeShift project, which employed a silicone- and acrylic-based dielectric elastomer to trigger the motion of the skin (Rossi, Augustynowicz, Georgakopoulou, & Sixt, n.d.).

The determinant property when analysing the suitability of these materials for innovative adaptive façade system application was the required electrical current (control) to achieve a reversible deformation (quantitative value of the response). From Fig. 8, it can be seen that a large amount of energy is necessary to produce a meaningful shrinkage deformation, which makes questionable the use of piezoelectric and electroactive polymers if the aim is to reduce the energy demand of the building.

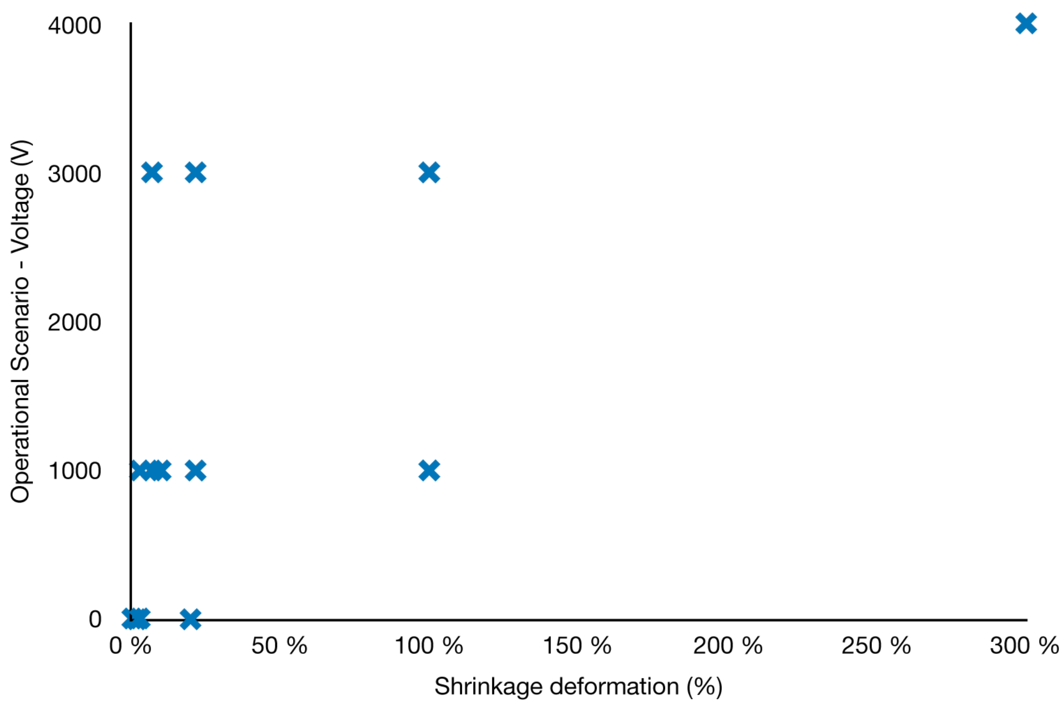


FIG. 8 Required electrical current to achieve certain level of shrinkage deformation for some electroactive materials

4.4 REVERSIBLE EXPANSION AND POSSIBLE BENDING

Electroactive polymers can also reversibly bend due to the electrical charges. The current generates the attraction of the opposing charges and the repelling forces between equal charges, and as a result, the thickness of the polymer contracts while it expands in length. Moreover, there are several materials that could provide this bending reaction, for instance, shape memory polymers and shape memory alloys reversibly change their shape (in one or more directions) when they reach an operational temperature; this is due to thermal-elastic transformations at molecular levels.

Apart from the aforementioned Smart Materials, there are some Multifunctional Materials that were designed to achieve the desired bending under specific environmental conditions (Table 1). Thermobimetals, for example, are composed of two metal sheets that have different coefficients of thermal linear expansion, which makes the composite material bend when it is exposed to a temperature gradient (Adriaenssens et al., 2014). Bi-layer hygromorph composites are also based on the same principle, but their differences in the coefficient of linear expansion are based on their capacity to absorb ambient humidity (Reichert et al., 2015).

SMART MATERIAL FAMILY	SPECIFIC MATERIAL	MULTIFUNCTIONAL MATERIAL FAMILY	SPECIFIC MATERIAL
Electroactive Polymers	Silicone and acrylic based dielectric elastomer(Rossi et al., n.d.), Polyvinylidene fluoride (PVDF) (Madden, 2008)	Thermobimetal	ASTM TM2 bimetal, Ni-Fe alloy (Adriaenssens et al., 2014) (containing 41%, 37% and 36% Nickel) (Kanthal, n.d.)
Shape Memory Polymers	Polymer Resin Systems, Polystyrene (Markopoulou, 2015; materia, n.d.-b; MatWeb Material Property Data, n.d.), Composite from multiple photocurable Methacrylate based copolymer network (Ge et al., 2016)	Hygromorphs	Bi-layer composites Ex. Composite mixture of glass fibre, epoxy bonding and Maple wood (Reichert et al., 2015)
Shape Memory Alloy	Ni-Ti alloy (55%-56% Nickel and 44%-45% Titanium) (Dynalloy, Inc., n.d.; Madden, 2008)		

TABLE 1 Autoreactive materials which have the ability to reversibly expand and bend

For the consideration of their possible application in façade engineering, the main restriction was their adaptability range. In the reviewed literature, we found several materials in other fields that change their shape by bending, but as we already explained in Section 2, we only compiled those that deformed by at least at a centimetre.

4.5 MOISTURE ABSORPTION

Hydrogels (Table 2) are well-known hygro-expansive materials, as they have the ability to dramatically increase their volume when they absorb moisture (Raviv et al., 2014). They could constitute actuator devices for kinetic façades that aim to respond to humidity variations, which might have some benefits in the hygrothermal performance (Markopoulou, 2015).

SMART MATERIAL FAMILY	SPECIFIC SMART MATERIAL	MULTIFUNCTIONAL MATERIAL FAMILY	SPECIFIC MULTIFUNCTIONAL MATERIAL
Hydrogel	Hydrophilic UV curable polymer(Raviv et al., 2014), Polymers of hydroxyethyl, Insoluble polymers of acrylate, Insoluble polymers of acrylamide, Insoluble polymers of polyethylene oxide(Markopoulou, 2015)	Hydrothermally solidified soil bodies	Sepiolite clay, Allophane (Emile, 2002; Watanabe et al., 2008), Earth ceramics
		Natural Porous materials	Cedar (Emile, 2002), Silica gel, Mixture of gibbsite and clay material(Watanabe et al., 2008), Mesoporous material derived from kaolinite, Meso-porous material derived from metakaolinite(Maeda & Ishida, 2009)

TABLE 2 Autoreactive materials triggered by ambient humidity

In addition, the academic literature on moisture absorption and passive cooling has revealed the emergence of new multifunctional materials that could control the hygrothermal conditions of the indoor environment (Maeda & Ishida, 2009; Watanabe et al., 2008). Inspired by the suitable performance of natural porous materials in humid and hot climate conditions, hydrothermally solidified soil bodies were developed in such a way that the porosity of their micro-structure could enable the self-regulation of the water content in the surrounding air through capillary condensation. However, as far as the authors know, there are no experimental validations that prove this assessment and they should be instigated in order to discover the potential of these promising multifunctional materials for their application on interior claddings.

5 DISCUSSION AND CONCLUSION

5.1 MEANINGFUL PHYSICAL PROPERTIES

Adequate performance of the façade must be ensured by each element of the system. SMs and MMs need to provide a suitable adaptive reaction while accomplishing traditional façade requirements regarding safety, economy, and comfort. Furthermore, materials need to behave optimally during their whole service-life. The physical properties of such materials determine whether they can perform properly in the proposed role. For instance, some of these materials might be required to fulfil structural performances, so their structural properties, such as compressive strength, bending strength, or elastic modulus need to be appropriate. If they were to perform kinetic work, then performed work, elastic modulus, and fatigue life would be fundamental. Finally, depending on their position in the façade system and the relationships with the other building materials, fire resistance and fire containment, rain and water-vapour resistance, thermal properties, and fenestration properties would be required.

Nevertheless, as we are not expecting the same behaviour for a coating and for a metal sheet, firstly, the material family needs to be detected, so that we can determine what kind of performance can be demanded from a particular type of material. After that, according to their performance in the whole façade system, specific properties are sought. In general, commercially available adaptive façade materials provided the meaningful physical properties in their data-sheets, but when analysing materials used in other fields, it was not possible to find out this technical information.

5.2 TOWARDS PROMISING NEW ROLES

Most of the Smart and Multifunctional Materials shown in this paper were sophisticated raw materials, highly engineered or designed. However, they could be used to develop simple façade products as, by applying them, it wouldn't be necessary to make intricate details including complex electronics or mechanical actuators. Still, there are few examples in architecture that include Smart or Multifunctional Materials, and even fewer built façades. Thus, it was difficult to get accurate, essential technical information regarding specific façade requirements and meaningful dynamic operation parameters. Nowadays, smart glazing is technologically the most advanced and new roles beyond are yet to be explored. Moreover, a wide variety of Multifunctional Materials could be created, inspired by promising reactions of Smart Materials. As their complexity comes mainly from the design process instead of their raw material availability or engineering process, overcoming this intellectual challenge could inspire a great opportunity to achieve new functionalities in architecture.

5.3 FURTHER RESEARCH

Overall, more experimental assessments are needed in order to get indispensable information regarding design characteristics, dynamic operation, and physical properties, as, so far, only a few responsive materials available in the building industry make their technical information available. Furthermore, assessments should be done at building scale, as these materials might behave unexpectedly and the value of their reaction might be non-linear at different scales (Kolarevic, 2014). Last but not least, more information on suitable operational scenarios and optimal scales of adaptability would help us to establish a greater degree of accuracy on this matter.

Acknowledgements

This paper is the output of the Short Term Scientific Mission entitled "The-state-of-the-art of adaptive and multifunctional materials", funded by COST Action TU1403 "Adaptive Façade Network". It was developed as part of the Working Group 1 and within the Façade Research Group (FRG) of the Department of Architectural Engineering + Technology, Delft University of Technology (TU Delft). It is also part of the ongoing PhD research project titled "Adaptive Opaque Façades: a design and assessment method", funded through a scholarship granted by Asociación de Amigos of the Universidad de Navarra.

References

Addington, D. M., & Schodek, D. L. (2005). *Smart materials and new technologies : for the architecture and design professions.* Amsterdam: Elsevier, Architectural Press.

Adriaenssens, S., Rhode-Barbarigos, L., Kilian, A., Baverel, O., Charpentier, V., Horner, M., & Buzatu, D. (2014). Dialectic form finding of passive and adaptive shading enclosures. *Energies*, *7*(8), 5201–5220. http://doi.org/10.3390/en7085201

Cabeza, L. F., Castell, A., Barreneche, C., De Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews*, *15*(3), 1675–1695. http://doi.org/10.1016/j.rser.2010.11.018

Dynalloy, Inc. (n.d.). Retrieved March 23, 2018, from http://www.dynalloy.com/tech_data_ribbon.php

Emile, I. (2002). Soil-Ceramics (Earth), Self-adjustment of Humidity and Temperature. *Encyclopedia of Smart Materials*. Wiley.

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *Renewable and Sustainable Energy Reviews*, *55*, 863–884. http://doi.org/10.1016/j.rser.2015.10.086

Fraunhofer Institute for Applied Polymer Research IAP. (n.d.). Retrieved March 23, 2018, from https://www.iap.fraunhofer.de/content/dam/iap/en/documents/FB2/Solardim_ECO_Fraunhofer-IAP.pdf

Gavrilyuk, A., Tritthart, U., & Gey, W. (2007). Photo-stimulated proton coupled electron transfer in quasi amorphous WO3 and MoO3 thin films. *Philosophical Magazine*, *87*(29), 4519–4553. http://doi.org/10.1080/14786430701561516

Ge, Q., Sakhaei, A. H., Lee, H., Dunn, C. K., Fang, N. X., Dunn, M. L., ... Qi, H. J. (2016). *Multimaterial 4D Printing with Tailorable Shape Memory Polymers. Scientific Reports* (Vol. 6). http://doi.org/10.1038/srep31110

Granqvist, C. G. (2014). Electrochromics for smart windows: Oxide-based thin films and devices. *Thin Solid Films*, *564*, 1–38. http://doi.org/10.1016/j.tsf.2014.02.002

Ibañez-Puy, M., Bermejo-Busto, J., Martín-Gómez, C., Vidaurre-Arbizu, M., & Sacristán-Fernández, J. A. (2017). Thermoelectric cooling heating unit performance under real conditions. *Applied Energy*, *200*, 303–314. http://doi.org/10.1016/j.apenergy.2017.05.020

Jiang, H., Kelch, S., & Lendlein, A. (2006). Polymers move in response to light. *Advanced Materials*, *18*(11), 1471–1475. http://doi.org/10.1002/adma.200502266

Juaristi, M., Monge-Barrio, A., Sánchez-Ostiz, A., & Gómez-Acebo, T. (2018). Exploring the potential of Smart and Multifunctional Materials in Adaptive Opaque Façade Systems. *Journal of Façade Design and Engineering; Vol 6 No 2: ICAE2018 Special IssueDO - 10.7480/Jfde.2018.2.2216*.

Kanthal. (n.d.). Retrieved March 23, 2018, from https://www.kanthal.com/en/search/?q=bimetal

Kolarevic, B. (2014). Adaptive Architecture: Low-Tech, High-Tech or Both? In M. Kretzer & L. Hovestadt (Eds.), *ALIVE : Advancements in adaptive architecture.* (p. 220). Basel/Berlin/Boston: Birkhäuser,.

Kornbluh, R. (2008). *Fundamental configurations for dielectric elastomer actuators. Dielectric Elastomers as Electromechanical Transducers*. Elsevier Ltd. http://doi.org/10.1016/B978-0-08-047488-5.00008-3

Kretzer, M. (2017). *Information Materials*. Springer International Publishing AG Switzerland. http://doi.org/10.1007/978-3-319-35150-6

Kretzer, M., & Hovestadt, L. (2014). *ALIVE : Advancements in adaptive architecture.* (NV-1 o). Basel/Berlin/Boston : Birkhäuser,.

Lampert, C. M. (2003). Large-area smart glass and integrated photovoltaics. *Solar Energy Materials and Solar Cells*, *76*(4), 489–499. http://doi.org/10.1016/S0927-0248(02)00259-3

Laughlin, Z., & Howes, P. (2012). *Material Matters: New Materials in Design*. United Kingdom, Europe: Black Dog Publishing Ltd.

LCRHallcrest. (n.d.). Retrieved March 23, 2018, from https://www.hallcrest.com

Lin, S., & Theato, P. (2013). CO2 -Responsive polymers. *Macromolecular Rapid Communications*, *34*, 1118–33. http://doi.org/10.1002/marc.201300288

Loonen, R. C. G. M., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, *25*, 483–493. http://doi.org/10.1016/j.rser.2013.04.016

López, M., Rubio, R., Martín, S., Croxford, B., & Jackson, R. (2015). Active materials for adaptive architectural envelopes based on plant adaptation principles. *Journal of Façade Design and Engineering*, *3*(1), 27–38. http://doi.org/10.3233/FDE-150026

Ma, Y., & Zhu, B. (2009). Research on the preparation of reversibly thermochromic cement based materials at normal temperature. *Cement and Concrete Research*, *39*(2), 90–94. http://doi.org/10.1016/j.cemconres.2008.10.006

Madden, J. D. W. (2008). *Dielectric elastomers as high-performance electroactive polymers. Dielectric Elastomers as Electromechanical Transducers*. Elsevier Ltd. http://doi.org/10.1016/B978-0-08-047488-5.00002-2

Maeda, H., & Ishida, E. H. (2009). Water vapor adsorption and desorption of mesoporous materials derived from metakaolinite by hydrothermal treatment. *Ceramics International*, *35*(3), 987–990. http://doi.org/10.1016/j.ceramint.2008.04.007

Markopoulou, A. (2015). Design Behaviors ; Programming Matter for Adaptive Architecture. *Next Generation Building 1*, *1*, 57–78. http://doi.org/10.7564/15-NGBJ17

materia. (n.d.-a). Retrieved March 23, 2018, from https://materia.nl

Materiability. (n.d.-a). http://doi.org/http://materiability.com

Materiability. (n.d.-b). Retrieved March 23, 2018, from http://materiability.com/portfolio/thermochromics/

Materiability. (n.d.-c). Retrieved April 9, 2018, from http://materiability.com/wp-content/uploads/2014/09/m_06.jpg

Materiability. (n.d.-d). Retrieved March 23, 2018, from http://materiability.com/portfolio/thermobimetals/

MatWeb Material Property Data. (n.d.). Retrieved March 23, 2018, from http://www.matweb.com/search/datasheettext.aspx?matguid=da5f0f16f66446a38bce7b1ee4fe2c61

Mlyuka, N. R., Niklasson, G. A., & Granqvist, C. G. (2009). Thermochromic multilayer films of VO2 and TiO2 with enhanced transmittance. *Solar Energy Materials and Solar Cells*, *93*(9), 1685–1687. http://doi.org/10.1016/j.solmat.2009.03.021

QCR Solutions Corp. (n.d.). Retrieved March 23, 2018, from http://www.qcrsolutions.com/Site/Home___QCR_Solutions_Corp.html

Raviv, D., Zhao, W., McKnelly, C., Papadopoulou, A., Kadambi, A., Shi, B., … Tibbits, S. (2014). *Active Printed Materials for Complex Self-Evolving Deformations*. *Scientific reports* (Vol. 4). http://doi.org/10.1038/srep07422

Reichert, S., Menges, A., & Correa, D. (2015). Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. *CAD Computer Aided Design*, *60*, 50–69. http://doi.org/10.1016/j.cad.2014.02.010

Rossi, D., Augustynowicz, E., Georgakopoulou, S., & Sixt, S. (n.d.). ShapeShift. Retrieved March 23, 2018, from http://caad-eap.blogspot.com.es

Samatham, R., Kim, K. ., & Dogruer, H. . (2007). Active Polymers: An Overview. In J. K. Kwang & S. Tadokoro (Eds.), *Electroactive Polymers for Robotic Applications* (pp. 1–36). London: Springer.

Seeboth, A., Ruhmann, R., & Mühling, O. (2010). Thermotropic and thermochromic polymer based materials for adaptive solar control. *Materials*, *3*(12), 5143–5168. http://doi.org/10.3390/ma3125143

Smart Films International. (n.d.). Retrieved March 23, 2018, from http://smartfilmsinternational.com/solar-glass/#thermo_glass_download

Watanabe, O., Fukumizu, H., & Ishida, E. H. (2008). Development of an Autonomous Humidity Controlling Building Material, 19–29.

Zhang, Y., Lee, S. H., Mascarenhas, A., & Deb, S. K. (2008). An UV photochromic memory effect in proton-based WO3 electrochromic devices. *Applied Physics Letters*, *93*(20), 10–12. http://doi.org/10.1063/1.3029775

Possibilities and Challenges of Different Experimental Techniques for Airflow Characterisation in the Air Cavities of Façades

Emanuela Giancola[1*], M. Nuria Sánchez[1], Matthias Friedrich[2], Olena Kalyanova Larsen[3], Alessandro Nocente[4], Stefano Avesani[5], Francesco Babich[5], Francesco Goia[4]

* Corresponding author
1 Ciemat, Department of Energy, Energy Efficiency in Buildings Unit, Spain, emanuela.giancola@gmail.com
2 HafenCity University Hamburg, Germany
3 Aalborg University, Denmark
4 Norwegian University of Science and Technology, Norway
5 Eurac Research, Institute for Renewable Energy, Italy

Abstract

Ventilated façades are applied in both new and existing buildings. It has been claimed that these components help to reduce energy use in buildings and improve occupant comfort. However, their performance strongly depends on the airflow passing through the cavity. In order to characterise and to model the behaviour of the ventilation and its effectiveness, the components need to be tested in the laboratory, as well as under real dynamic weather conditions. Despite the steadily growing research in this area, there are few studies with conclusive results about the reliability of existing experimental procedures for characterisation of airflow in the ventilated cavities. The aim of this paper is to describe and review recent state of the art experimental assessments for the airflow characterisation in ventilated cavities. The paper starts with a short introduction on the potentialities and limitations of different experimental methodologies, and continues with a detailed classification and description of the most relevant monitoring techniques for airflow in air cavities of façades that have been developed in recent years.

Keywords

façade characterisation, experimental techniques, airflow monitoring, tracer gas, velocity profile, ultrasound, pressure difference, PIV, LDV, temperature profile & heat flux

DOI 10.7480/jfde.2018.3.2470

1 INTRODUCTION

A comfortable and hygienic indoor climate is one of the fundamental requirements expected of the building envelope. One method of coping with the need to reduce cooling loads through the envelope is to make use of a natural or mechanically induced airflow in the cavity of the façade (Lee, Sang, Yeo, & Kim, 2009). Even if there are many synonyms for the term 'ventilated façade' - such as active façade, double envelope, rain screen, or double skin façades (DSF) - which correspond (more or less) to different configurations, all of these terms refer to a building envelope system characterised by a ventilated layer. Currently, innovative building elements perform one or more of the several functions that a building envelope is required to do, but the assessment of their effectiveness is a complex task. The functions of façade systems to be tested are now more numerous (and more complex) than those traditionally assessed through conventional metrics (such as the U-value, or the g-value). In particular, when it comes to ventilated façades, the assessment of the performance is often connected to the assessment of the airflow rate. However, the on-site (and laboratory) characterisation of the airflow in a ventilated façade is not a trivial task. Although the European standard, EN 16211-2015 'Ventilation for buildings - Measurement of air flows on site – Methods', provides a description of the air flow methods and outlines how measurements are performed to achieve the stipulated measurement uncertainties, the implementation of these methods in a ventilated façade is not straightforward. There is therefore a clear need to define a robust and repeatable procedure for characterising the performance of ventilated façade, which goes hand in hand with the need to develop suitable facilities for research, development, and testing of façades (Cattarin et al., 2018; Goia, Schlemminger, & Gustavsen, 2017).

The performance of the ventilated façade has been evaluated both numerically and experimentally in multiple studies (López, Jensen, Heiselberg, Ruiz de Adana Santiago, 2012; Sanjuan, Suarez, Gonzalez, Pistono, & Blanco, 2011; Suarez, Joubert, Molina, & Sanchez, 2011). The experimental evaluations have been developed in different scenarios: real buildings, outdoor test cells, and indoor laboratories. Despite the differences between numerical predictions and experimental data, all results demonstrate a marked reduction in summer thermal loads due to the induced ventilation airflow. In-depth experimental analysis of this system will enable the updated model to better reproduce the façade energy savings and air quality conditions inside the building.

Following the classification proposed by Cattarin, Causone, Kindinis, and Pagliano (2016), the assessment of façade systems may be performed by means of three main types of test rig: outdoor real-scale facilities, outdoor test cells, and laboratory indoor facilities. The major constraints of field measurements are: a) the complexity of isolating a single variable (Serra, Zanghirella, & Perino, 2010); b) the difficulty in comparing the measured data with other available data sets, due to the unique architectural features of each real-scale building and the boundary conditions; c) the complexity of achieving a high level of instrumentation and control necessary for accurate performance assessment (Strachan & Vandaele, 2008). Instead, the tests carried out in controlled laboratory conditions give the possibility to carefully check the most influential parameters, such as ambient temperature, heating of the outer skin of the façade, relative humidity, and air velocity, as well as the possibility to test the influence of each parameter individually. Laboratory experiments are carried out under steady state or, where appropriate, dynamic boundary conditions with pre-defined test sequences. The effects of one or more meteorological conditions are sometimes imitated through dynamic programs, but these cannot fully reproduce the complex interactions of pure stochastic processes typical of real climate, as well as of some characteristics of the outdoor boundary conditions (such as, for example, the geometrical component of solar irradiation on the façade). Over the last decades, all types of mentioned experimental cells/facilities have contributed to the present state of the art in façade characterisation. However, different experimental methods for characterisation of the airflow in ventilated cavities can be used, depending on the geometry of the ventilated façade, peculiarities of the experimental cell, type of airflow, equipment at hand etc.

The determination of the airflow in the naturally ventilated cavities is a key and challenging issue. The influence of airflow, however, has not been studied to the same extent. The lack of an overview of different established procedures for collection of experimental data for naturally ventilated cavities (Dama, Angeli, & Kalyanova Larsen, 2017) is the main reason for the present state of the art. Measuring and predicting airflow are difficult tasks due to the stochastic nature of the wind. As reported by Perino et al. (2008), one of the main problems of uncertainty in the estimation of the airflow is determined by the wind conditions and by the thermal behaviour of the façade. An increase of airflow rate in the cavity will reduce the temperature difference between the exterior and the air in the cavity. As a result, the airflow rate will diminish. This 'self-regulating' interaction is reported by Saelens (2002).

The number of existing experimental methods for estimation of airflow rate in the built environment is limited to the following: tracer gas measurements, velocity profile method, and ultrasound measurement of velocity, as well as the use of models with measured pressure differences across the opening (Hitchin & Wilson, 1967) and the temperature profile along the ventilated cavities. Furthermore, the laser-based non-intrusive experimental techniques of Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) (Sánchez, Sanjuan, Suárez, & Heras, 2013) are applied to determine indoor airflow behaviour. The air change rate of naturally induced airflow is significantly different in occupied spaces compared to façade cavities. However, there are no experimental methods specifically developed for ventilated cavities, and thus the traditional ones for occupied spaces are used. The scope of this paper is therefore to raise awareness about this problem and call for comparative investigations on existing experimental techniques, with a particular focus on naturally ventilated cavities, as well as on the development of specific guidelines for this purpose.

2 CLASSIFICATION AND REVIEW OF EXISTING EXPERIMENTAL TECHNIQUES FOR AIRFLOW CHARACTERISATION IN THE AIR CAVITIES OF FAÇADES

The intention of this section is to provide the reader with a comprehensive understanding of the experimental techniques for airflow characterisation of ventilated cavities, their possibilities and limitations. The key features of each technique are summarised in Table 1 at the end of this section.

2.1 TRACER GAS MEASUREMENTS

Tracer gas measurements for determining airflow rates in buildings are frequently applied (Laussmann & Helm, 2011). There are three established tracer gas techniques that can be found in the literature: decay, constant concentration, and constant emission (Etheridge, 2011). Looking at the applicability of each of these techniques in ventilated cavities, a constant emission method is normally used, although there are a number of limitations that contribute to high uncertainty of the results obtained using this method. By recording the concentration of tracer gas in a defined volume (e.g. a room) and considering the background concentration, as well as the tracer gas supply, the air change rate can be calculated. The tracer gas is initially assumed to be equally distributed throughout the whole space. However, this assumption is limited in ventilated spaces as there will be a lower concentration near the fresh air supply and exhaust openings, and a higher concentration in the deeper part of the room (horizontal gradient) (Larsen, 2006). In contrast to naturally ventilated occupied spaces, the application of the tracer gas method with constant emission in a ventilated façade brings additional uncertainty to the experimental estimation of naturally induced airflow. In the first place, this is caused by the stochastic behaviour of the wind and therefore the irregular dilution of the tracer gas, but the uncertainty is further increased by the lack of research within the field. Until now, there have been no clear guidelines established with regard to the application of tracer gas methodology in ventilated façades, since the effect of positioning the emission source within the ventilated cavity, as well as the number and location of tracer gas dilution measurement points on measurement accuracy remain unknown.

Marques da Silva, Gomes, and Moret Rodrigues (2015) tested different positions for tracer gas emission and concentration sampling points. Overall, the results show no clear tendency, as the airflow in the cavity is highly dynamic. The knowledge about flow dynamics of cavities is low and therefore no preferable position was found. Kalyanova, Jensen, and Heiselberg (2007) found that tracer gas emission near the supply air opening of a cavity can cause a 'wash-out effect' where the gas is flushed out near the opening before it can mix with the cavity air, resulting in an inaccurate (too high) airflow rate. Other sources of inaccuracies are found due to reverse flow and recirculation effects. Nevertheless, the tracer gas method is one of the best available options, due to the lack of good alternatives, relatively simple installation of sensors, and minimal required instrumentation.

2.2 VELOCITY PROFILE

The measurement of the air velocity is a means by which to determine the airflow rates and to estimate the surface convective heat transfer coefficient. Both these two variables are very relevant for the calculation of the façade air cavity performances and therefore the direct measurement of the air velocity is of great interest. Nevertheless, the air velocity spatial differences can vary substantially in the three-dimensional field, depending on the air cavity geometry and on the airflow regime. Consequently, the air velocity field is difficult to characterise or generalise by physical or empirical equations for all façade air cavities. The air velocity profile method allows for the assessment of the façade air cavity performance through the measurement of the air velocity at some characteristic points.

2.2.1 Experimental setup

Different types of anemometers can be used for punctual determination of air velocity. These devices must be able to detect high frequency fluctuations in transient air flow. The hot-wire and the hot-sphere anemometer are the most frequently used instruments in façade-related applications (Belleri, Avantaggiato, & Lollini, 2017; López et al., 2012; Manz, Schaelin, & Simmler, 2004; Mateus, Pinto, & Graça, 2014; Park, Augenbroe, Messadi, Thitisawat, & Sadegh, 2004), mainly because of their fast responses and velocity range between 0-5 m/s. The definition of the experimental layout in terms of number and position of the anemometers across and along the air cavity is a trade-off between reducing their number, lowering the air channel obstruction, and increasing the measurement points to better appreciate the velocity variation. The sensors must be located at a reasonable distance from any obstruction. One further relevant factor to be considered in defining the experimental setup is the influence of the solar radiation on the temperature-based measurement principle (e.g. hot-sphere) as discussed by Jensen, Kalyanova, and Hyldgaard (2007). An example of experimental set-up in an outdoor test bench can be found in Kalyanova et al. (2007).

2.2.2 Main challenges encountered in design and operation

The main challenge in applying this method is the reduction of the cavity cross section due to the probes, cables, and fixing system, as well as deficiency of the method in detecting the direction of the air streams (upward or downward). Larsen (2006) performed a measurement of the velocity profile in a naturally ventilated, wide cavity, where it is documented that due to high velocities in the boundary layer, a large number of measurement points in the boundary layer are necessary in order to build an accurate velocity profile. Accordingly, the measurement accuracy becomes a trade-off between a number of measurement points and the disturbances that are introduced into the experimental domain. Furthermore, the presence of upward and downward air streams poses problems in the design of the experimental set-up. Jensen et al. (2007) investigated a method to determine the flow direction by using two hot sphere anemometers. However, determination of flow direction at one point is not enough for an accurate estimation of the whole cavity airflow, as in the case of two-directional flow occurrences. A second relevant challenge is the choice of probes features. The uncertainty of the hot-wire measurement system normally varies depending on the inverse of the velocity module. On the contrary, for naturally ventilated cavities, high accuracy at low velocity is requested.

Finally, the experimental layout must be designed starting from the specific façade geometry and expected airflow regime. Consequently, the design of a good experimental layout is very challenging as it would require the extensive use of CFD simulations.

2.2.3 Limitation of the experiment

The main limitation of the experiment is the need for a detailed analysis of the airflow characteristics, due to the high 3D variability of the air velocity field. Consequently, a punctual measurement of the air velocity carries very limited information on the air cavity airflow regime. As a result, both the number and the location of the sensors need to be optimised.

2.3 ULTRASOUND MEASUREMENT OF VELOCITY

The use of sound waves in the ultrasound range is a well-established technique for the measurement of (volumetric) flows in ducts and pipes and for the measurement of wind velocity (2D, 3D) in the field of environmental monitoring. Though the principles on which this measurement technique is based have been known for a long time (Suomi, 1957), the development of sensors for HVAC applications is rather recent (Strauss, Weinberg, & Kopel, 1996) with ongoing research activities in the field of device development (Raine, Aslam, Underwood, & Danaher, 2015).

This class of measurement techniques, which makes use of the interaction of (ultrasonic) sound waves with the moving fluid to determine the average velocity along the path of the sound wave (Cuerva & Sanz-Andrés, 2000) is primarily based on two alternative concepts, to which correspond two different devices: the Doppler effect ultrasonic flow meter and the transit time ultrasonic flow meter.

2.3.1 Doppler shift flow meter

These devices are based on the measurement of the frequency shift between a sound wave and its reflection caused by the particles in the flow. The flow rate is analytically determined, knowing the thermophysical properties and state properties, based on the Doppler effect equation, by processing the signals from the transmitter and the receiver. It is necessary that the fluid under analysis is able to reflect ultrasonic waves due to small bubbles of gas (in the case of a liquid) or the presence of eddies in the flow stream.

2.3.2 Transit time flow meter

These devices are based on the contemporary emission/reception of two identical sound waves between two couples of emitter/receiver, where one emitted/received soundwave travels downstream and the other upstream of the direction of the fluid flow. In the case of a still air mass, the transit time in each direction is identical, while under a flowing volume the downstream sound wall travels faster than the upstream one, and the difference between the two velocity values increases with the flow rate. The transmitter analytically calculates the average velocity of the flow rate based on the difference in the transit time across the two sound paths.

2.3.3 Main challenges encountered in design and operation

The use of ultrasonic principle for airflow monitoring presents several advantages: a) it can handle a very wide range of velocity, under different flow regimes; b) it is non-intrusive and does not influence the fluid flow; c) one sensor measures the average velocity across a section of the façade/duct, and multiple directions can be measured if more sensors are installed; d) because of the use of the difference between two velocity values, the procedure is independent from the temperature and pressure conditions of the fluid. When it comes to limitations and challenges, it is worth mentioning that the accuracy of this technique is reduced with very low air velocity. Accuracy is also reduced for cavities that are too deep or too thin, but the technique seems to be well suited to measuring airflows in cavities in the approximate range of 0.1m to 0.5m.

When more sensors are installed in the same cavity, and are close to each other, different frequencies for each sensor might be necessary to avoid incorrect readings. The implementation of this technique in a ventilated façade is not an established procedure and there may be challenges that are unknown at present, and which will be experienced only after several tests with this technique have been carried out.

2.3.4 Limitation of the experiment

The accuracy of this measurement method is relatively good and can be in the range of 2 -5% of the measured values. However, in the case of extremely low velocity (range of 10^{-2} m/s) the uncertainty can become far higher, and almost in the range of the measured values. Research activities are definitely necessary to deepen the applicability of this technique to façade systems due the poor literature in the field. Requirements in terms of developed flow regime are to be investigated, due the lack of standardised procedures for the application of ultrasonic sensors.

2.4 MEASURED PRESSURE DIFFERENCE

In theory, a pressure difference across an opening of naturally ventilated façade reflects the airflow rate induced by wind and buoyancy. More exactly, a relationship between the pressure difference and the airflow passing through the opening can be expressed as an equation (1) where Q is air flow (m^3/h), ΔP is pressure difference (Pa), and a, b are empirically obtained coefficients. Coefficients a and b depend on the shape of the opening itself and therefore the resistance that it initiates into the air passage.

$$Q = a \cdot \Delta P^b$$

This theory is used as a background for the pressure difference methodology for airflow measurement of naturally induced airflow, which is comparable to the measurement of the airflow in mechanically ventilated spaces using an orifice method. The method includes two stages: the calibration of the opening and the actual measurement. In contrast to the relatively accurate orifice method, little progress was made with regard to the pressure difference method, in terms of accuracy evaluation, as well as in terms of its practical application.

At present, there is only one known example of this method application. In Kalyanova et al. (2007) it is used in the full-scale outdoor test facility 'Cube', where the results of this method are found to be disappointing for the natural airflow, but relatively successful when the cavity is mechanically ventilated. The main finding of this work is that the method is very sensitive to the positioning of the surface pressure and reference measurement, to the fluctuations in wind direction and wind speed. Thus, further research is needed to establish a suitable methodology for the pressure difference measurement in a naturally ventilated cavity as it gives strong inspiration for finding a way to cope with the extremely high wind fluctuations and thereby fluctuations of the airflow.

2.5 PARTICLE IMAGE VELOCIMETRY (PIV)

PIV is an optical method of flow visualisation and quantification of instantaneous velocity fields, measuring two velocity components in an area of analysis by adding small tracer particles. Different suitable materials and particle generators are used. Seeding particles are selected to ensure acceptable flow tracking and adequate light scattering efficiency. However, determining optimal particle size is more critical in turbulent flows and high-speed gas flows since the particle's motion is more complex to treat. 2D-PIV has become a common technique used in research studies based on PIV, though a more complex PIV setup based on stereoscopic flow field analysis (Stereo-PIV) has been used increasingly in recent years (Sánchez, Giancola, Suárez, Blanco, & Heras, 2017). The latter enables the measurement of the out of plane velocity component. Currently, the new concept of volumetric velocimetry (TOMO PIV) enables the measurement of the three velocity components in a volume.

2.5.1 Experimental setup

- A constructed ventilated façade model is simplified but designed considering the basic structure of real ventilated façades with the three main components: an exterior layer creating open joints, an inner layer, and an air chamber created between both coatings. A heating mat system is installed and well-adhered to the outside of the outer layer.

- Laboratory indoor facilities:
  - A fully-equipped lab with a double cavity pulsed laser, charge-coupled device cameras generating sets of images downloaded onto a PC, a Laser Pulse Synchroniser acting as an external trigger to control the whole system, and a six jet atomiser which generates tracer particles.
  - Additionally, temperature sensors and an infrared thermographic camera are used to perform different temperature measurements.

2.5.2 Main challenges encountered in design and operation

The PIV technique requires a strong initial investment in human and financial resources. The equipment is sophisticated and quite expensive, as is its regular maintenance and upgrading. Additionally, laboratory personnel must be specialised in handling PIV equipment and its complex methodology. The design of the façade model presents multiple challenges. It is important to ensure the versatility and easy assembly of the model, dividing it into multiple components that can be easily exchanged.

Several challenges are faced because the experimental evaluation of the ventilated cavity is performed in laboratory conditions. Experimental limitations are mainly linked to the specific requirements of the PIV technique, the dimensions of the laboratory, and the reproduction of real environmental conditions. A major challenge of the experiment is to emulate the effect of incident solar radiation on the panels.

Regarding the operation of experimental PIV measurements, the limited size of the measurement area of the CCD cameras does not enable the capturing of the airflow evolution inside the ventilated camera in a single experimental run.

2.5.3 Limitation of the experiment

A major limitation of this technique is to simulate wind effect on airflow inside the ventilated cavity. Solar heat load effects are also critical with respect to façade performance. Solar radiation outdoor conditions are usually reproduced in the laboratory by using heating mats over the exterior layer.

2.6 LASER DOPPLER VELOCIMETRY (LDV)

The LDV or Laser Doppler Anemometry (LDA) is a laser-based optical method for velocity measurement in transparent or semi-transparent fluids. Invented by Yeh and Cummins (1964), it is based on the Doppler shift in a laser beam scattered by a particle (added as seeding or normally present in the flow).

2.6.1 Experimental setup

A monochromatic laser beam is divided in two in a Bragg cell, a device that uses the opto-acoustic effect to introduce a frequency shift in one of the beams. Each beam is then separated into three colours and each addressed to the probe. Here, a lens focuses the beams which collide in the measurement volume where the interference creates a series of fringes. When a particle crosses the fringes, it will scatter the light with a Doppler frequency proportional to its velocity in the three spatial directions. Since the frequency shift generates a known motion in the fringes, it is possible to resolve the sign of the velocity in each direction.

As with all the optical techniques, the LDV is not invasive (Moureh, Tapsoba, & Flick, 2009). A laser blade is not necessary, therefore the optical access is easier and there are no flare problems introduced by the blade sides (Wuibaut, Bois, El Hajem, Akhras, & Champagne, 2006).

2.6.2 Main challenges encountered in design and operation

The velocity is measured directly, with a linear response, and there is no need for calibration procedures. The accuracy is very high, due to the small dimension of the measurement volume, and the system has a better signal-to-noise ratio if compared to PIV since it does not require the analysis of artificially created images. Nevertheless, LDV measures one point at the time while PIV can reveal the global structure of the flow, which is useful in the research of flow mechanism. Special care needs to be taken regarding the accuracy of the traverse system for the placement of the probe and the optical setup (Zhang & Eisele, 1995). This assumes an even higher importance is given to 3D measurements, where one of the three couples of beams is focused by a second probe. In addition, the location of the measurement volume must be carefully evaluated, and it must be taken into account the possible influence that curved surfaces have on the reflection of the laser beam (Eisele, Zhang, Casey, Gulich & Schachenmann, 1997).

Typical application of LDV is in flow research such as aerodynamics of vehicles, water flow measurements, spray and combustion characterisation, as well as in automation, and lately in hemodynamics. The technique was successfully applied by Bhamjee, Nurick, and Madyira (2013) to the study of airflow in ventilated windows in cases of forced and natural flow.

2.7 TEMPERATURE PROFILE AND HEAT FLUX METHOD. REAL SCALE FACILITY

Real-scale facilities realise a large variety of full scale façade prototypes built on a large-scale test building (Marinosci, Semprini, & Morini, 2014) or in a real building (Fantucci, Marinosci, Serra, & Carbonaro, 2017; Giancola, Sanjuan, Blanco, & Heras, 2012). The enthalpy discharge linked to the airflow within the ventilated cavity directly affects the reduction of the heat flux across the inner wall; for this, the measure of the temperature profile is a means by which to quantify this effect. The data presented in literature indicates that for fixed weather conditions, to guarantee the lower thermal load entering the building, the measured temperature within the cavity must be the lower maximum value.

2.7.1 Experimental setup

In literature, the following variables are measured along the façade: air temperature in the middle of the ventilated cavity at different heights; surface temperature of the external layer and surface temperature of the insulated façade at different heights; velocity and direction of the wind next to the façade; heat fluxes at the interior and at the exterior surfaces of the inner mass wall; relative humidity and global radiation on the horizontal surface; global and infrared radiation on the façade surface; ambient temperature. Sensors are placed on the centreline of the façade at different heights above the floor. The surface temperature sensors are placed inside the ventilated cavity and are exposed to occasional handling as well as to climatic conditions. Consequently, open-wire thermocouples of cooper-constantan type (T) are used. The surface temperatures inside the ventilated cavity are measured using bare sensors covered with a reflecting tape to prevent possible errors due to surface-to-surface radiation heat fluxes. The heat flux through the internal mass wall is measured with plane fluxmeters. The heat flux is measured at the inside surface and at the exterior surface of the inner mass wall.

2.7.2 Main challenges encountered in design and operation

The main challenges encountered in design and operation are the accuracy of the sensors and the measurement chain, as the assumptions included in the monitoring aim affect the overall uncertainty of the performance indicators. Experiments carried out in real-scale facilities are usually designed to evaluate the overall energy performance of the building. In addition, real-scale facilities present many more limitations which restrict their field of applicability.

2.7.3 Limitation of the experiment

A major limitation is due to longer testing periods than steady-state laboratory tests. Real-scale facilities are exposed to the external environment conditions that affect material degradation for which they require continuous maintenance and care. Another limitation is the lack of a standardised procedure.

Technique	Physical principle	Application			Type of measurements	Intrusive		Measured Physical Quantity	Usual Accuracy	Technical complexity	Investment
		Real scale	Test Cell	Laboratory		Yes	No				
Tracer gas (Constant emission)	Conservation of mass (air and tracer gas)	X	X	X	Single points or volume	X		Concentration of tracer gas to obtain air ventilation rate	Low	Low	Low
Velocity Profile	Temperature-based measurement sensors	X	X	X	Single points	X		Air velocity	Low	Low	Low
Ultrasound **a) Doppler shift flow meter** **b)Transit time flow meter**	a) Frequency shift between sound wave and its reflection b) Transit time in fluid flow of identical sound waves upstream vs downstream	X	X	X	Plane		X	The interaction of ultrasonic sound waves with the moving fluid to obtain air velocity	Medium	Medium	Low
Pressure Difference	Relation between the pressure difference and the airflow passing through an opening		X	X	Single points	X		Air pressure difference to obtain airflow rate	Low	Low	Low
PIV	Cross-correlation between consecutive images of laser light scattered by tracer particles			X	Plane or volume		X	Particle images displacement over a given time interval between consecutive two laser pulses to obtain air velocity field	Very High	High	Extremely High
LDV	Doppler shift in a laser beam scattered by a particle	X[1]	X[1]	X	Single points		X	Doppler frequency of scattered light proportional to particles velocity	High	High	Extremely High

>>>

Temperature Profile and Heat Flux method	Enthalpy discharge	X	X	X		X		Ambient and surface Temperature Heat Flux Relative Humidity Global Radiation on the horizontal surface Global and Infrared Radiation on the facade surface	Low	Low	Low

TABLE 1 Key features of each experimental techniques for airflow characterization of ventilated cavities

[1] *If the amount of naturally occurring seeding particle (i.e. dust) is sufficient*

3 CONCLUSIONS

The experimental evaluation of the airflow rates in ventilated façades is proven not to be a straightforward task. Until now, the experimental methods developed specifically for characterising ventilation in buildings and airflow in ducts were applied for measurements on ventilated façades. This is one of the reasons why there are few studies with conclusive results about the reliability of existing experimental procedures for the characterisation of airflow in the ventilated cavities. There is, therefore, a need to raise awareness on the lack of knowledge and robust procedures to assess the airflow in a ventilated façade. This paper has therefore the intention of stimulating:

- further testing of existing methods in order to evaluate their accuracy for application with ventilated cavities;
- the development of common guidelines and generally acknowledged measurement procedures for application with ventilated façades; and
- the development of new methods suitable for application with ventilated cavities.

In this paper, a description and a review of the recent state of the art of the experimental assessments for the airflow characterisation in ventilated cavities was presented. The classification is based on laboratory tests, as well as under real dynamic weather conditions. The tests carried out in a controlled laboratory give the possibility to carefully check all the most influential parameters. The number of existing experimental methods for the estimation of airflow rate in the built environment is limited to the following: tracer gas measurements, velocity profile method, and ultrasound measurement of velocity, as well as the use of models with measured pressure differences and the temperature profile along the ventilated cavities. Furthermore, the laser-based non-intrusive experimental techniques of Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) are applied to determine indoor airflow behaviour. Potentialities and limitations as well as a detailed classification and description of such monitoring techniques for airflow in façades air cavities have been reported.

Considering the applicability of each of the tracer gas measurement techniques in ventilated cavities, a constant emission method is normally used. Until now, no clear guidelines have been established with regard to the application of tracer gas methodology in ventilated façades, as the effect of positioning the emission source within the ventilated cavity, as well as number and location of tracer gas dilution measurement points on measurement accuracy remain unknown. Overall, the results show no clear tendency as the airflow in the cavity is highly dynamic. The measurement of the air velocity is a means by which to determine the airflow rates and to estimate the surface convective heat transfer coefficient.

The air velocity profile method allows the assessment of the façade air cavity performance from the measurement of the air velocity at some characteristic points. The main limitation of the experiment is the need for a detailed analysis of the airflow characteristics, especially in airflows with high 3D variability of the air velocity field. The use of the ultrasonic principle for airflow monitoring presents several advantages, for example: it's non-intrusive and does not influence the fluid flow. The accuracy of this measurement method is relatively good and can be in the range of 2 - 5% of the measured values. Research activities are definitely necessary to advance in their effective implementation to façade systems, paying special attention to the requirements in terms of developed flow regime. Currently, the results of pressure difference method application to a ventilated cavity are successful in mechanically ventilated cavities but differ considerably in natural airflows.

The main finding of this work is that the method is very sensitive to the positioning of the surface pressure and reference measurement, and to the fluctuations in wind direction and wind speed. Thus, further research is needed to establish a suitable methodology for the pressure difference measurement in a naturally ventilated cavity, as it gives strong inspiration for finding a way to cope with the extremely high wind fluctuations and thereby fluctuations of the airflow. A major limitation in real-scale facilities is the testing time, longer than normal testing periods in laboratory. Also, resulting from its environmental exposure, material rapidly becomes degraded and ongoing maintenance is required.

All previous techniques have the common drawback of measuring over single points or single sections instead of a field or a volume to characterise the three-dimensional behaviour of the air velocity field. Consequently, previous measurement methodologies need to be further developed, determining optimal points of measurement set up to balance low intrusiveness in airflow with adequate spatial resolution.

The non-intrusive ultrasound PIV on the contrary, allows detailed analysis of the airflow variability. However, the important initial financial investment and the technical complexity might be an obstacle to their widespread application. A major limitation of this technique is the simulation of wind effect on airflow inside the ventilated cavity. Solar heat load effects are also critical with respect to façade performance.

Acknowledgements
The authors acknowledge the networking opportunities given by the Cost Action TU1403 "Adaptive Facades Network".

References

Belleri, A., Avantaggiato, M., & Lollini, R. (2017). Ventilative Cooling in Shopping Centers' Retrofit: The Mercado Del Val Case Study. *Energy Procedia 111*, pp. 669-677

Bhamjee, M., Nurick, A., & Madyira, D. M. (2013). An experimentally validated mathematical and CFD model of a supply air window: Forced and natural flow. *Energy and Buildings 57*, pp.289-301

Cattarin, G., Causone, F., Kindinis, A., & Pagliano, L. (2016). Outdoor test cells for building envelope experimental characterisation - A literature review, *Renewable and Sustainable Energy Reviews 54*, pp.606-625

Cattarin, G., Pagliano, L., Causone, F., Kindinis, A., Goia, F., Carlucci, S., & Schlemminger, C. (2018). Empirical validation and local sensitivity analysis of a lumped-parameter thermal model of an outdoor test cell. *Building and Environment 130*, pp. 151–161

Cuerva, A., & Sanz-Andrés, A. (2000). On sonic anemometer measurement theory. *Journal of Wind Engineering and Industrial Aerodynamics 88* (1), pp.25-55

Dama, A., Angeli, D., & Kalyanova Larsen, O. (2017). Naturally ventilated double-skin façade in modeling and experiments. *Energy and Buildings 144*, pp.17–29

Eisele, K., Zhang, Z., Casey, M. V., Gulich, J., & Schachenmann, A. (1997). Flow analysis in a pump diffuser—part 1: LDA and PTV measurements of the unsteady flow. *Journal of Fluids Engineering 119(4)*, pp.968-977

Etheridge, D. (2011). *Natural Ventilation of Buildings: Theory, Measurement, and Design*. Hoboken, New Jersey: John Wiley & Sons, pp. 428

EUROPEAN STANDARD, (2015). Ventilation for buildings - Measurement of air flows on site – Methods. NS-EN 16211, European Committee for Standardization, Brussels, Belgium

Fantucci, S., Marinosci, C., Serra, V., & Carbonaro, C. (2017). Thermal Performance Assessment of an Opaque Ventilated Façade in the Summer Period: Calibration of a Simulation Model through in-field Measurements. *Energy Procedia 111*, pp.619-628

Giancola, E., Sanjuan, C., Blanco, E., & Heras, M. R. (2012). Experimental assessment and modelling of the performance of an open joint ventilated façade during actual operating conditions in Mediterranean climate, *Energy and Buildings 54*, pp.363-375

Goia, F., Schlemminger, C., & Gustavsen, A. (2017). The ZEB Test Cell Laboratory. A facility for characterization of building envelope systems under real outdoor conditions. *Energy Procedia 132*, pp. 531-536

Hitchin, E. R., & Wilson, C. B. (1967). A Review of Experimental Techniques for the Investigation of Natural Ventilation in Buildings. *Building Science 2*, pp.59-82

Jensen, R. L., Kalyanova, O., & Hyldgaard, C. E. (2007). On the use of hot-sphere anemometers in a highly transient flow in a double-skin façade. *Proceedings of Roomvent 2007. FINVAC ry*, Helsinki, Finland

Kalyanova, O., Jensen, R. L., & Heiselberg, P. (2007) Measurement of air flow rate in a naturally ventilated double skin façade. *Proceedings of Roomvent 2007. FINVAC ry*, Helsinki, Finland

Larsen, T. S. (2006). *Natural Ventilation Driven by Wind and Temperature Difference.* (DCE Thesis). Department of Civil Engineering, Aalborg University, Aalborg, Denmark

Laussmann, D., & Helm, D. (2011). Air Change Measurements Using Tracer Gases. In Mazzeo, N. (eds.) *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*, pp. 365-406. InTechOpen, Rijeka, Croatia doi: 10.5772/18600

Lee, S., Sang, H. P., Yeo, M. S., & Kim, K. W. (2009). An experimental study on airflow in the cavity of a ventilated roof. *Building and Environment 44*, pp.1431–1439

López, F. P., Jensen, R. L., Heiselberg, P., & Ruiz de Adana Santiago, M. (2012). Experimental analysis and model validation of an opaque ventilated facade. *Building and Environment 56*, pp. 265-275

Manz, H., Schaelin, A., & Simmler, H. (2004). Airflow patterns and thermal behavior of mechanically ventilated glass double façades. *Building and Environment 39 (9)*, pp. 1023-1033

Marinosci, C., Semprini, G., & Morini, G.L. (2014). Experimental analysis of the summer thermal performances of a naturally ventilated rainscreen façade building. *Energy and Buildings 72*, pp.280-287

Marques da Silva, F., Gomes, M. G., & Moret Rodrigues, A. (2015). Measuring and estimating airflow in naturally ventilated double skin facades. *Building and Environment 87*, pp.292-301

Mateus, N. M., Pinto, A., & Graça, G. Cd. (2014). Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell. *Energy and Buildings 75(0)*, pp.511-522

Moureh, J., Tapsoba, M., & Flick, D. (2009). Airflow in a slot-ventilated enclosure partially filled with porous boxes: Part I–measurements and simulations in the clear region. *Computers & Fluids 38(2),* pp.194-205

Perino, M., Serra, V., Zanghirella, F., Issoglio, R., Marques da Silva, F., & Gomes, M.G. (2008) Performance evaluation of advanced integrated façades in laboratory facilities. *Proceedings of 29th International AIVC Conference*, Kyoto, Japan

Park, C. S., Augenbroe, G., Messadi, T., Thitisawat, M., & Sadegh, N. (2004). Calibration of a lumped simulation model for double-skin façade systems. *Energy and Buildings 36*, pp. 1117-1130

Raine, A.B., Aslam, N., Underwood, C.P., & Danaher, S. (2015). Development of an Ultrasonic Airflow Measurement Device for Ducted Air. *Sensors 15*, pp.10705-10722

Saelens, D. (2002). *Energy performance assessment of single storey Multiple-Skin Facades.* (Doctoral Thesis) Laboratory for Building Physics, Department of Civil engineering, Catholic University, Leuven, Belgium

Sánchez, M. N., Sanjuan, C., Suárez, M. J., & Heras, M. R. (2013). Experimental assessment of the performance of open joint ventilated façades with buoyancy-driven airflow. *Solar Energy 91*, pp.131-144

Sánchez, M. N., Giancola, E., Suárez, M. J., Blanco, E., & Heras, M. R. (2017). Experimental evaluation of the airflow behaviour in horizontal and vertical Open Joint Ventilated Facades using Stereo-PIV. *Renewable Energy 109*, pp.613-623

Sanjuan, C., Suarez, M. J., Gonzalez, M., Pistono, J., & Blanco, E. (2011). Energy performance of an open-joint ventilated façade compared with a conventional sealed cavity façade, *Solar Energy 85 (9)*, pp.1851-1863

Serra, V., Zanghirella, F., & Perino, M. (2010). Experimental evaluation of a climate façade: energy efficiency and thermal comfort performance, *Energy and Buildings 42*, pp.50-62

Strachan, P.A., & Vandaele, L. (2008). Case studies of outdoor testing and analysis of building components. *Building and Environment 43*, pp. 129–42

Strauss, J., Weinberg, H., Kopel, Z. (1996). *U.S. Patent 5,583,301*: Ultrasound Air Velocity Detector for HVAC ducts and method therefor

Suarez, C., Joubert, P., Molina, J. L., & Sanchez, F. J. (2011). Heat transfer and mass flow correlations for ventilated facades, *Energy and Buildings* 43, pp.3696-3703

Suomi, V.E. (1957). *Sonic Anemometer, Exploring the Atmosphere's First Mile, Vol. 1*. New York: Pergamon Press, pp.356–366

Wuibaut, G., Bois, G., El Hajem, M., Akhras, A., & Champagne, J. (2006). Optical PIV and LDV comparisons of internal flow investigations in SHF impeller. *International Journal of Rotating Machinery, vol. 2006*

Yeh, Y., & Cummins, H. (1964). Localized fluid flow measurements with an He–Ne laser spectrometer. *Applied Physics Letters,* 10(4), pp.176–178

Zhang, Z., & Eisele, K. (1995). Off-axis alignment of an LDA-probe and the effect of astigmatism on measurements. *Experiments in fluids 19(2),* pp.89-94

Thermal Assessment of Glass Façade Panels under Radiant Heating: Experimental and Preliminary Numerical Studies

Chiara Bedon[1*], Marcin Kozłowski[2,3], Dániel Honfi[4]

* Corresponding author
1 University of Trieste, Italy, chiara.bedon@dia.units.it
2 Lund University, Sweden
3 Silesian University of Technology, Poland
4 RISE - Research Institutes of Sweden, Sweden

Abstract

Nowadays, glass is increasingly being used as a load-bearing material for structural components in buildings and façades. Different structural member solutions (such as panels, beams, columns) and loading conditions were the subjects of several research studies in recent years. Most of them, however, were typically limited to experimental testing and numerical simulations on glass elements and assemblies at room temperature. Thermo-mechanical investigations, inclusive of the temperature-dependent behaviour of visco-elastic interlayers used in laminated glass solutions, as well as the typical thermo-mechanical degradation of glass properties in line with temperature increase, in this regard, are still limited. Such an aspect can be particularly important for adaptive façades, in which the continuous variation of thermal and mechanical boundary conditions should be properly taken into account at all the design stages, as well as during the lifetime of a constructed facility. Given the key role that thermo-mechanical studies of glazing systems can pe use of glass in façades, this paper focuses on Finite Element (FE) numerical modelling of monolithic and laminated glass panels exposed to radiant heating, by taking advantage of past experimental investigations. In the study discussed herein, being representative of some major outcomes of a more extended research project, one-dimensional (1D) FE models are used to reproduce the thermal behaviour of selected glass specimens under radiant heating, as observed in the past experiments. Given the high computational efficiency but very basic assumptions of 1D assemblies, a critical discussion of experimental-to-numerical comparisons is then proposed for a selection of specimens.

Keywords

monolithic glass, laminated glass, thermal loading, radiant heating, experimental testing, Finite Element (FE) numerical modelling

DOI 10.7480/jfde.2018.3.2477

1 INTRODUCTION

Façade systems, both traditional and innovative (i.e. adaptive façades that have been gaining widespread attention recently), are subjected to a multitude of boundary and loading conditions over their lifetime, including thermal and mechanical variations. In this regard, the system behaviour, especially for adaptive façades, should be properly assessed by giving careful consideration to several loading combinations, since these are responsible for degradation phenomena at material, component, and assembly level (Bedon, 2017; Bedon et al., 2018c). This is especially true when considering structural issues for façades in general, where both full-scale experiments and Finite Element (FE) numerical models that are able to capture the actual material and assembly behaviours are often required.

In this paper, the thermo-mechanical performance of glass façade panels is the subject of preliminary investigation, via experimental testing and simplified FE numerical methods. Glass, as commonly known, is largely used in engineering applications as a structural material, especially in the form of laminated sections composed of multiple glazing layers, bonded together by thermoplastic foils (see for example (Haldimann, Luible, & Overend, 2008; Feldmann et al., 2014)). However, major issues in the design of structural glazing assemblies are represented by the high sensitivity of glass and common bonding layers to temperature variations.

In recent years, several research studies have focused on the thermal and optical assessment, or energy performance evaluation, of several types of glazing assemblies and solutions, both at the component and at the whole building level (see for example Fang, Eames, & Norton, (2007); Ghosh, Norton, & Duffy (2016); Ghoshal & Neogi, (2014); Li, Li, Zheng, Liu, & Lu (2015); Aguilar et al. (2017); Parra, Guardo, Egusquiza, & Alavedra (2017), etc.).

From a structural point of view, the thermal performance of glass elements and systems directly reflects upon their load-bearing capacity, due to the intrinsic material properties (see Bedon (2017), for example, for a state-of-the-art review on load-bearing structural glass systems under fire). The key role of appropriate thermo-mechanical investigations is further enforced in the case of adaptive façades, rather than in traditional static curtains, where glass components could be further affected by continuous variations in both the thermal and mechanical boundary conditions (Favoino, Jin, & Overend, 2014; Hasselaar & Looman, 2007; Aldawoud, 2017; Baumgärtner, Krasovsky, Stopper, & von Grabe, 2017; etc.). On one side, given a daily or accidental/extreme temperature variation, thermal shock phenomena occurring after moderate/high thermal gradients can cause changes that exceed the strength of the glass, leading to opening and propagation of cracks, with loss of the structural integrity (Cuzzillo & Pagni, 1998; Tofilo & Delichatsios, 2010; etc.). Glass systems, due to the typically low material resistance and low thermal conductivity (Haldimann et al., 2008), are particularly vulnerable to failure from thermal shock (see for example Fig. 1(a)).

At the same time, the degradation of mechanical properties of the glass brought about by high temperature (modulus of elasticity, tensile resistance, etc.) could severely affect the structural performance of such assemblies (see Fig. 1(b)). On the other hand, the well-known temperature/load-time dependent behaviour of viscoelastic interlayer and/or rubbery materials that are commonly used to bond together the glass panels, as well as to join the glass panels to the structural background (see (Haldimann et al., 2008)) can have crucial effects even under operational conditions. At the design stage, the combination of these multiple phenomena should be hence properly accounted for, for safe design purposes.

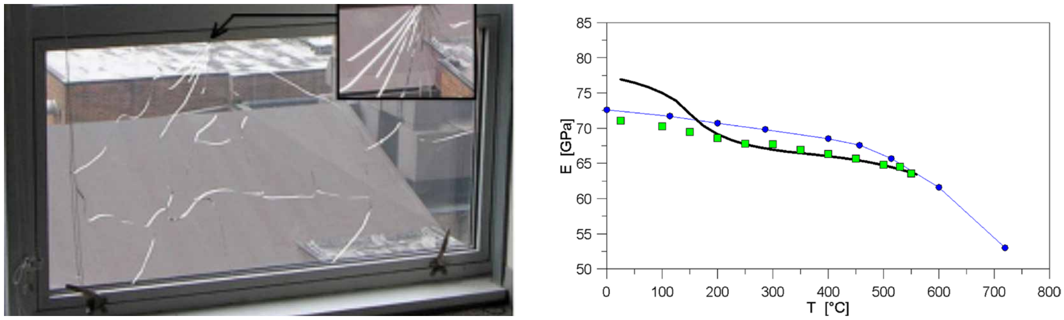


FIG. 1 Glass systems under thermal loading: (left) examples of thermal shock phenomena in a glass window and (right) experimental variation with temperature of the modulus of elasticity of ordinary glass *(figure adapted with permission from Bedon (2017) - plots are derived from different investigations)*

Experimental research studies have been focused, in the last few years, on the assessment of the thermo-mechanical performances of glass windows, façade systems, small-scale components subjected to high temperature scenarios and/or fire loading. Thermo-mechanical investigations on glazing systems, however, are indeed still limited in number and structural typology. An increasing interest is captured especially by the performance of structural glass components under fire, due to safety purposes. While full-scale experimental studies are still rare in the literature (see Bedon (2017) for an overview), numerical modelling can represent a robust tool and support for designers, as a further extension of time consuming and expensive testing. Key input parameters and possible limits in the same FE method, however, should be properly taken into account.

Bedon, Pascual Agullo, Luna-Navarro, Overend, & Favoino (2018b) numerically investigated the thermal and structural performance of glass-to-GFRP sandwich façade modular units, under ordinary thermal conditions and wind pressure. Although limited to specific loading configurations, the study suggested the importance of coupled thermal and mechanical simulations for a given glazing system, which should be preferably taken into account to optimise its overall performance. Bedon & Louter (2018) numerically investigated the load-bearing response of laminated glass plates under standard fire ISO curve and imposed mechanical loads. The numerical analyses generally gave evidence of a close correlation with test results, even suggesting the extension of the same study to a wide set of thermal-to-mechanical loading ratio conditions. At the same time, the mechanical restraints were found to have a crucial role in the overall performance of the same glass plates, both from the thermal and numerical points of view.

In this paper, numerical simulations are carried out in ABAQUS (Simulia) and proposed for both monolithic and laminated glass specimens under radiant heating, by means of geometrically simplified but computationally efficient one-dimensional (1D) assemblies. In doing so, the major advantage is taken from available experimental results, for small-scale glazing samples under thermal loading. Comparative results are then critically discussed, based on selected experimental results, in order to emphasise the potential and possible criticalities of the FE method. The research outcomes partly summarised in the paper are derived from two Short-Term Scientific Missions (STSMs) by the involved authors (WG2 - "Structural" Task Group members), which has been approved and financially supported, throughout 2018, by the EU-COST Action TU1403.

2 SUMMARY OF THE REFERENCE EXPERIMENTAL CAMPAIGN

The numerical analyses presented in this paper are based on the results of past experimental studies. Debuyser et al. (2017) carried out an experimental campaign that aimed to assess the thermal behaviour of annealed monolithic or laminated glass samples (annealed glass plies bonded together with PVB and SGP interlayers). In the reference study, glass panels with nominal dimensions of 185mm × 285mm were mounted in a supporting frame and exposed to radiant heating. See Fig. 2.

FIG. 2 Radiant panel tests *(debuyser, 2015; Debuyser et al., 2017)* (left); heat flux meters mounted on the frame, (right) testing of a sample

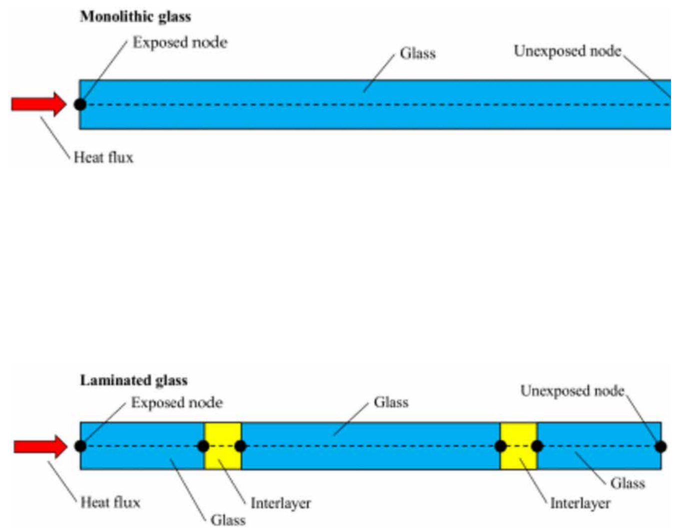
SAMPLE #	GLASS THICKNESS / BUILD-UP [MM]	INTERLAYER THICKNESS
T2	10 (MG)	-
T4	15 (MG)	-
T5	6+10+6 (LG)	0.76 mm (PVB)
T12	6+10+6 (LG)	0.76 mm (PVB)

TABLE 1 Overview of selected test specimens, according to *(Debuyser, 2015; Debuyser et al., 2017)*
Key: MG= monolithic glass, LG= laminated glass

The distance between the radiant panel and the typical glass specimen was about 450mm. All of the experiments started at an imposed air flow and gas flow of 8l/s and 0.475l/s, respectively. However, a time dependent decrease of the same gas flow (and hence of the corresponding heat flux) was generally observed during the tests. See Fig. 3.

Besides measuring the surface glass temperature (based on a set of thermocouples mounted both on the exposed and unexposed sides of each sample), the heat flux was also continuously monitored throughout the tests. This was done by means of Gardon gauge type sensors, which use a differential thermocouple as a transducer to measure the temperature difference between the centre and the circumference of a thin circular foil disc. The latter is bonded to a circular opening in a cylindrical heat sink. See Fig. 2(left).

Moreover, within the same experimental study, additional test measurements of thermal properties such as conductivity, diffusivity, and volumetric heat capacity of glass and PVB/SG interlayers were carried out. Further details of the tests results can be found in Debuyser (2015).



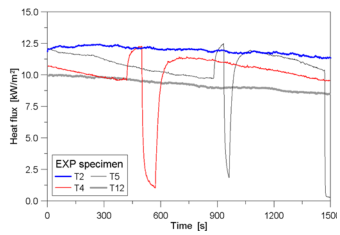


FIG. 3 Measured heat flux (at the side of the samples) for the selected tests specimens T2, T4, T5, and T12

FIG. 4 Schematic representation of 1D heat transfer models (ABAQUS). Typical view of (above) monolithic and (below) laminated glass specimens

From the total number of 16 specimens discussed in Debuyser, (2015) and Debuyser et al., (2017), four sets of glass samples were selected for the current study. In Table 1, the samples labelled as T2 and T4 represent monolithic glass panels with a thickness 10mm and 15mm, respectively. Specimens T5 and T12 are both laminated glass samples, composed of two external, 6mm thick glass plies each side of a central 10mm ply (0.76mm is the nominal thickness of the bonding PVB foils).

Fig. 3 presents the measured heat flux at the side. From the figure, slightly declining values of the heat flux for all specimen can be observed. The phenomenon is strictly related to the specifics of the radiant panel, in which constant heat flux was very difficult to obtain. Moreover, for the specimens T4 and T5 sudden drops of the heat flux at approx. 500s and 900s can be seen. These drops were caused by the unintentional overheating of the radiant panel, which was followed by the shutting off of the device. However, in these cases, the radiant panel was powered on again and the tests were continued.

3 NUMERICAL SIMULATIONS

The main aim of the numerical study summarised herein was to simulate the thermal behaviour of monolithic and laminated glass panels subjected to the assigned heat flux histories. In doing so, a one-dimensional (1D) heat transfer modelling approach was initially chosen, due to the well-known computational efficiency, in order to assess the potential and possible limits, compared to more advanced and refined (but time-consuming) full solid 3D models. The numerical results and comparisons discussed herein, in this regard, represent some major outcomes of an extended investigation. In the FE study, the set of samples summarised in Table 1 was numerically analysed by taking into account the experimental heat flux measured during the tests.

In accordance with the adopted 1D modelling approach, given a glass sample under thermal loading, the absorbed energy is conducted through the monolithic glass or through the different layers of the glass laminates, thereby causing a temperature increase within the materials. To describe this absorption and conduction, several temperature dependent thermal properties of both the glass and the interlayers are required, namely the specific heat capacity, the density, and the thermal conductivity. The temperature increase within the specimen is then estimated as the net result of the absorbed heat flux and the cooling heat fluxes. Therefore, the radiative and convective heat transfer to the environment are modelled at both the exposed surface and the back surface. The radiation to the environment requires the surface emissivity as input, and is assumed to be lumped at the surfaces of interest. The convection is then calculated as a function of the convective heat transfer coefficient. As the convective heat transfer coefficient is dependent on the nodal temperatures calculated within the given FE model, a user subroutine is required to describe its evolution (see Section 3.1). The basic assumption of such a FE modelling strategy is that three-dimensional effects (i.e. in-plane heat flux variations or in-plane temperature gradients, in combination with the imposed through-the-thickness heat flux) can be disregarded. The experimental-to-numerical comparisons are therefore reliable as long as the test temperatures from the past samples are measured in the central part of the glass panels, where the in-plane temperature gradient is negligible (see Section 2).

Careful consideration was given to the post-processing, especially for the FE analysis of the amount and evolution of temperature on the specimens' surfaces (both exposed and unexposed to the imposed heat flux), as well as the influence of heat flux history on the glass thermal response, including the temperature gradient DT in the thickness of each sample, throughout the simulation time. The latter aspect (manually calculated as the difference of temperature at the exposed and unexposed nodes) is a particularly important parameter because it is directly related to potential failure of glass due to thermal shock phenomena.

3.1 MODEL DESCRIPTION

A one-dimensional (1D) heat transfer model, analogous to the modelling approach presented in Debuyser (2015) and Debuyser et al. (2017), and further developed in Bedon, Honfi, & Kozłowski (2018a), was created using the commercial computer software ABAQUS (Simulia). The typical 1D model consisted of 2-node, one-dimensional diffusive heat transfer elements (type DC1D2, from ABAQUS element library), (Fig. 4). Temperature dependent thermal properties of glass and interlayers, such as conductivity and specific heat, were taken from references in literature (Tong, 1994; Cardenas, Leon, Pye, & Garcia, 2016; Debuyser, 2015). An optimal emissivity coefficient equal to 0.97 was then assumed for the glass surfaces, based on previous sensitivity studies (Bedon et al., 2018a). To define the thermal boundary conditions between the external glass nodes and the surrounding environment, a Fortran script user-subroutine was used. This involved a convective heat transfer coefficient dependent on the varying temperature of the exposed and unexposed nodes, as also described in detail in Debuyser (2015), Debuyser et al. (2017), and Bedon et al. (2018a). In doing so, long-wave radiative phenomena and related effects were neglected. While long-wave exchanges typically have a key role in energy balance simulations in buildings and require advanced numerical tools (see for example Stefanizzi, Wilson, & Pinney (1990) Miller, Thomas, Kämpf, & Schlueter (2015) etc.), they are mostly negligible and conventionally disregarded for thermo-mechanical engineering simulations on ordinary, soda lime silica glass systems (Tong, Zhu, Guo, & Ma, 2002; Wang, Wang, & Li, 2013; Wang & Wang, 2016; etc.). An initial ambient temperature of 20°C was applied to the typical FE model. In the simulations, additional physical constants were also taken into account, such as the Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^{-4}) and the absolute zero temperature (-273°C). The thermal exposure was finally simulated by applying a concentrated heat flux to the exposed node of each 1D model, by taking into account - for each sample - the heat flux histories from the experiments.

Sections 3.2 and 3.3 present some selected results for the monolithic and laminated glass samples object of investigation. There, continuous lines are conventionally used to represent the temperature evolution at the exposed node of each specimen ("Exp", in the following), while dashed lines are used for the unexposed node ("UnExp").

3.2 NUMERICAL RESULTS FOR MONOLITHIC GLASS SPECIMENS

Fig. 5 presents a comparison of numerical and experimental results for the 10mm thick monolithic glass specimen (T2, according to Table 1). In the past experiment, the specimen T2 was exposed to a constant heat flux slightly decreasing over time, (Fig. 3). Such a thermal loading typically resulted in a rather stable increase of temperature over time in the thickness of the sample(Fig. 5(a)).
In general, the FE model proved to offer a rather acceptable agreement with the corresponding test measurements. However, the numerical results were found to partly overestimate the experimental predictions. A close correlation was observed especially at the beginning of the temperature history (≈300s), at both the exposed/unexposed nodes. For the following instances of thermal exposure, the average scatter was found to grow to a maximum of 12%, which may be related to the input parameters assumed herein, and in particular the thermo-physical properties of glass.

Fig. 5(b), in this regard, shows a point-by-point comparison between the experimentally and numerically estimated temperatures, on both the exposed and unexposed faces of the T2 specimen. Input data are taken from selected time instants (0-1500s) and proposed in normalised form.
Given the linear trend of both the series of dots, it is possible to notice that through the full thermal exposure the numerical data estimate the experiments in the average value of 10% and 5%, at the exposed and unexposed nodes, respectively. The experimental-to-numerical correlation, in addition, has mostly a linear trend for both the reference control points, with major scatter in the range of 130-180°C only (approx. 300-500s).

Additional experimental-to-numerical results are finally proposed, for the same T2 sample, in Fig. 5(c), in the form of temperature gradient DT in the thickness of glass. As expected, the numerical results were observed to generally overestimate the experimental calculations, up to approx. 50% in some exposure intervals. Such a scatter, resulting from cumulative effects depicted in Fig. 5(b), was found to have a mostly uniform trend for the full time history. This effect could be caused by the input thermal parameters of glass, as previously highlighted, but also by possible defects of the measurement methods, as partly described by Bedon et al. (2018a). In terms of thermal cracking for the examined specimen, both the experimentally and numerically calculated temperature gradients DT are presented in Fig. 5(c) and lie below the allowable value of 45°C that the prEN thstr:2004 document recommends for annealed glass panels with polished edges (10mm the nominal thickness, as in the case of the T2 sample), to prevent thermal shock.

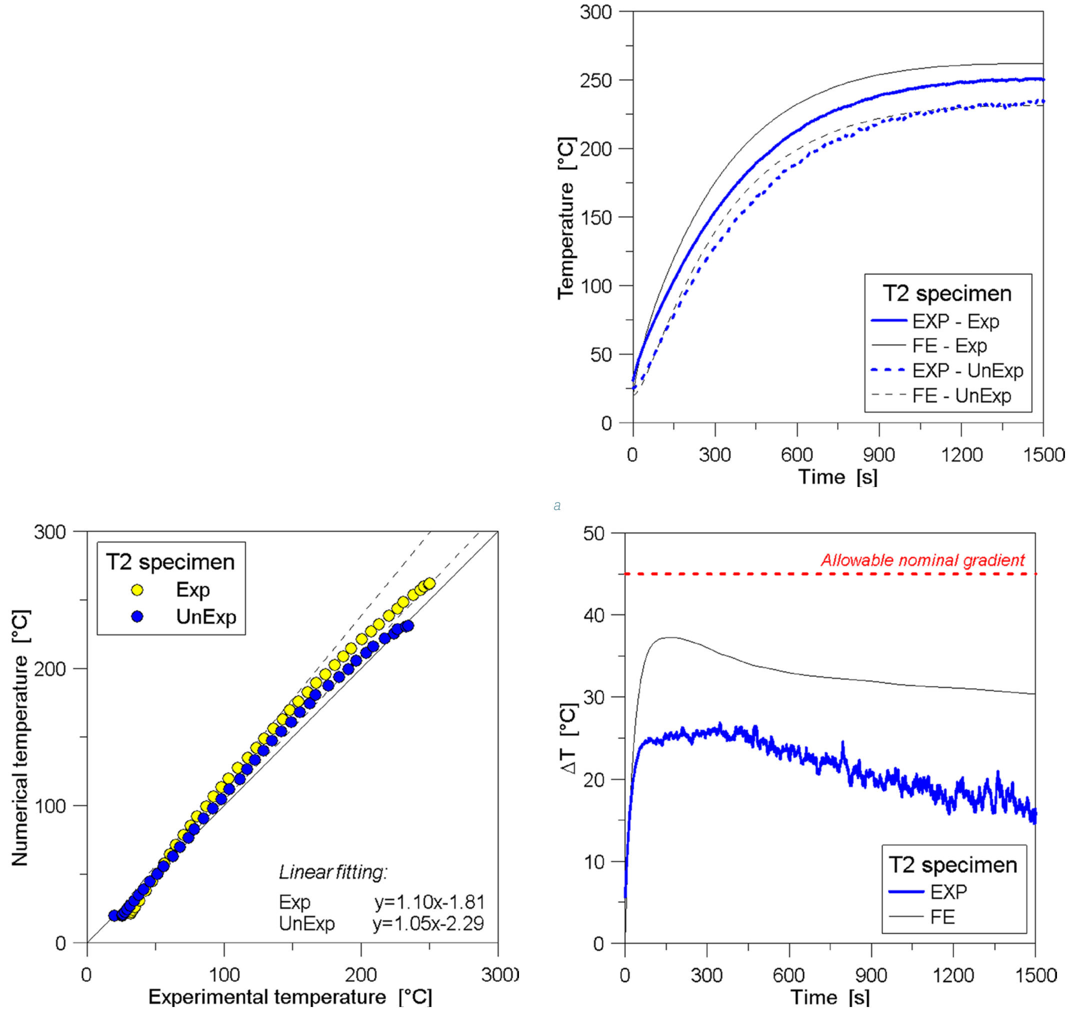


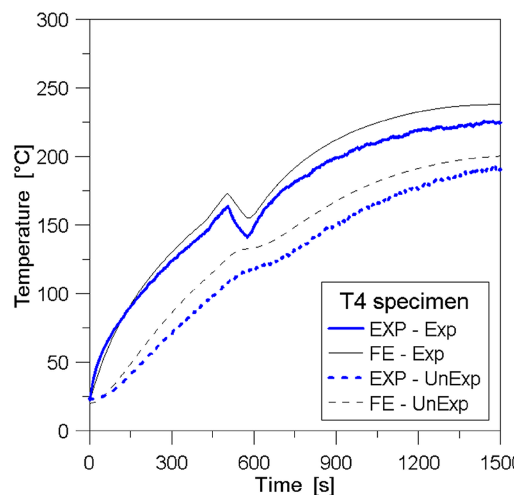
FIG. 5 Comparison between experimental and numerical (ABAQUS) results for the monolithic T2 sample: (a) temperature history and (b) point-by-point temperature comparisons for selected time instants, with (c) calculated temperature gradient, as a function of time

GLASS TYPE	LIMIT VALUES (°C)		
	As-cut or arrissed	Smooth ground	Polished
Float or sheets ≤12mm thick	35	40	45
Float 15mm or 19mm thick	30	35	40
Float 25mm thick	26	30	35
Patterned	26		
Wired patterned or polished wired glass	22		
Heat strengthened	100		
Tempered	200		
Laminated	Smallest value of the component panes		

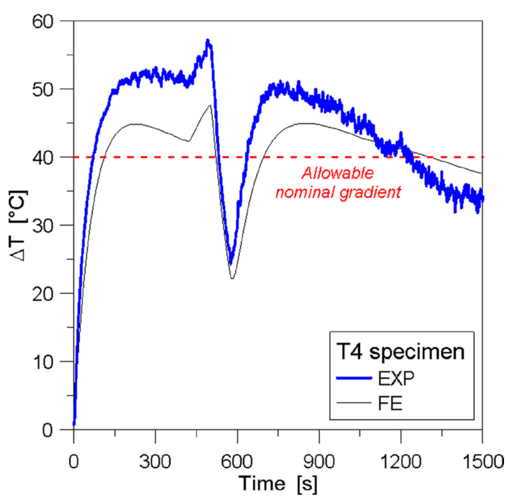
TABLE 2 Allowable temperature gradients, according to prEN thstr:2004 provisions

For clarity of presentation, Table 2 reports the actual reference values for different glass types and treatments, according to the same prEN thstr:2004 provisions. No major cracks due to thermal loading were observed during the experiment, even if limited damage propagation was noticed close to the sample supports, at the edge of the T2 panel, after 18min (≈1000s) of exposure). According to Fig. 5(c), such a time instant corresponds to a limited temperature gradient (≈22°C), hence suggesting further studies are necessary.

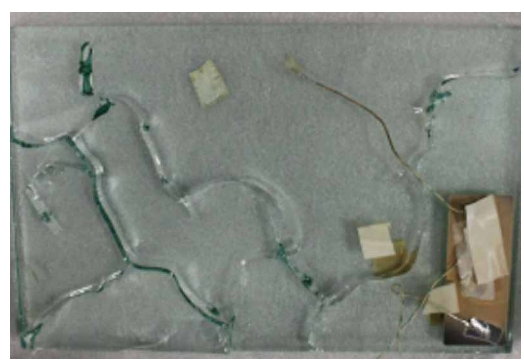
With the 15mm thick, monolithic specimen T4 being taken into account - with a difference from the T2 sample represented by the nominal thickness and the assigned radiant heating (Fig. 2, "T4 EXP" plot) - the temperature estimations proposed in Fig. 6 were obtained.



a



b



c

FIG. 6 Comparison between experimental and numerical (ABAQUS) results for the monolithic T4 sample: : (a) temperature history and (b) calculated temperature gradient, as a function of time, with (c) experimentally observed cracks in the sample

As in the case of the T2 specimen, the numerical results were generally observed to slightly overestimate the experimental data (Fig. 6(a)). For the FE node exposed to the heat flux, much better correlation was found, especially at the beginning of the temperature history (up to 600-700s), rather than at the later stage of the analysis (where, in any case, the FE temperature values exceed fewer than 10% the corresponding test results). In the case of the unexposed node, for the whole simulation time, the FE results were indeed found to overestimate the experimentally measured temperatures, by approximately 10%. For both the exposed and unexposed nodes, after ≈500s of thermal exposure, a drop in temperature can be also clearly observed, which was caused by a sudden shutting off of the radiant panel. Such a phenomenon is more evident on the exposed surface, while the unexposed node - due to the thermal inertia of glass volume - is less sensitive.

Fig. 6(b) shows the temperature gradient ΔT as a function of time, as calculated from the past experimental data and obtained from the numerical analysis of the T4 specimen. As shown, the numerical results were observed to underestimate the experiments until approximately 1200s of exposure, while, subsequently, the FE predictions overestimate the experiments. The measured and simulated ΔT was much larger than the allowable temperature gradient recommended by the prEN thstr:2004 provisions (i.e. 40°C for 15mm thick polished panels, see Table 2) and was typically associated - in the reference experiments – with severe cracks in the specimen, (Fig. 6(c)). Since the numerical gradient of Fig. 6(b) also rises up to ≈22°C, given the mechanical properties of glass (i.e. Fig. 1(b), etc.) and its sensitivity to temperature variations, it is also expected that the thermo-mechanical analysis of the same sample - typically requiring a time-temperature scenario for the FE model nodes as a key input parameter - could also result in crack propagation.

3.3 NUMERICAL RESULTS FOR LAMINATED GLASS SPECIMENS

Two selected laminated glass specimens were then taken into account from the full set of experimental samples, with the reference cross-section schematised in Fig. 7.

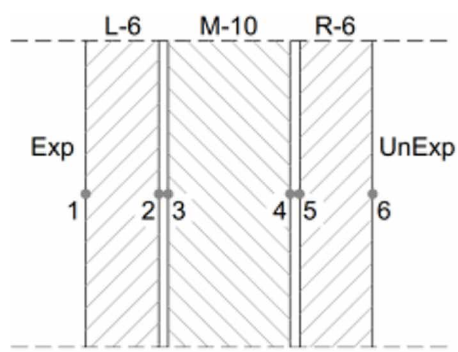


FIG. 7 Reference layered section for the laminated T5 and T12 specimens, with evidence of numerical control points

Fig. 8, in this regard, presents a comparison of numerical and experimental results for a laminated glass specimen composed of two 6mm plies and a middle 10mm ply (T5, see Table 1). Even moving from a monolithic to a layered cross-section, as also observed for the T2 and T4 results, much better agreement with the experiments was observed for the early stage of the FE analysis on the T5 assembly (600-700s). This included the evolution of temperature at both the exposed an unexposed nodes. During the reference experiment, similarly to the T4 sample, a sudden shutting off of the radiant panel took place at approx. 950s of exposure. Such an accident can be clearly perceived in the temperature histories shown in Fig. 8(a). Given the presence of multiple glass layers - compared to the T4 monolithic sample - it is, in any case, possible to notice that the temperature records were affected on the exposed surface only, with mostly null effects on the back face of the laminated assembly. Worth noting, finally, is that after 700-800s of exposure, the FE model generally proved to underestimate the test results for the exposed node (up to -15% their scatter at the final stage of the analysis). Conversely, the temperature evolution was overestimated for the unexposed glass layer (up to +30%, at the end of the analysis). A similar result could be derived both from the input thermal properties of glass and interlayers, as well as from the basic assumptions of the 1D models presented herein, hence suggesting the need for further extended investigations.

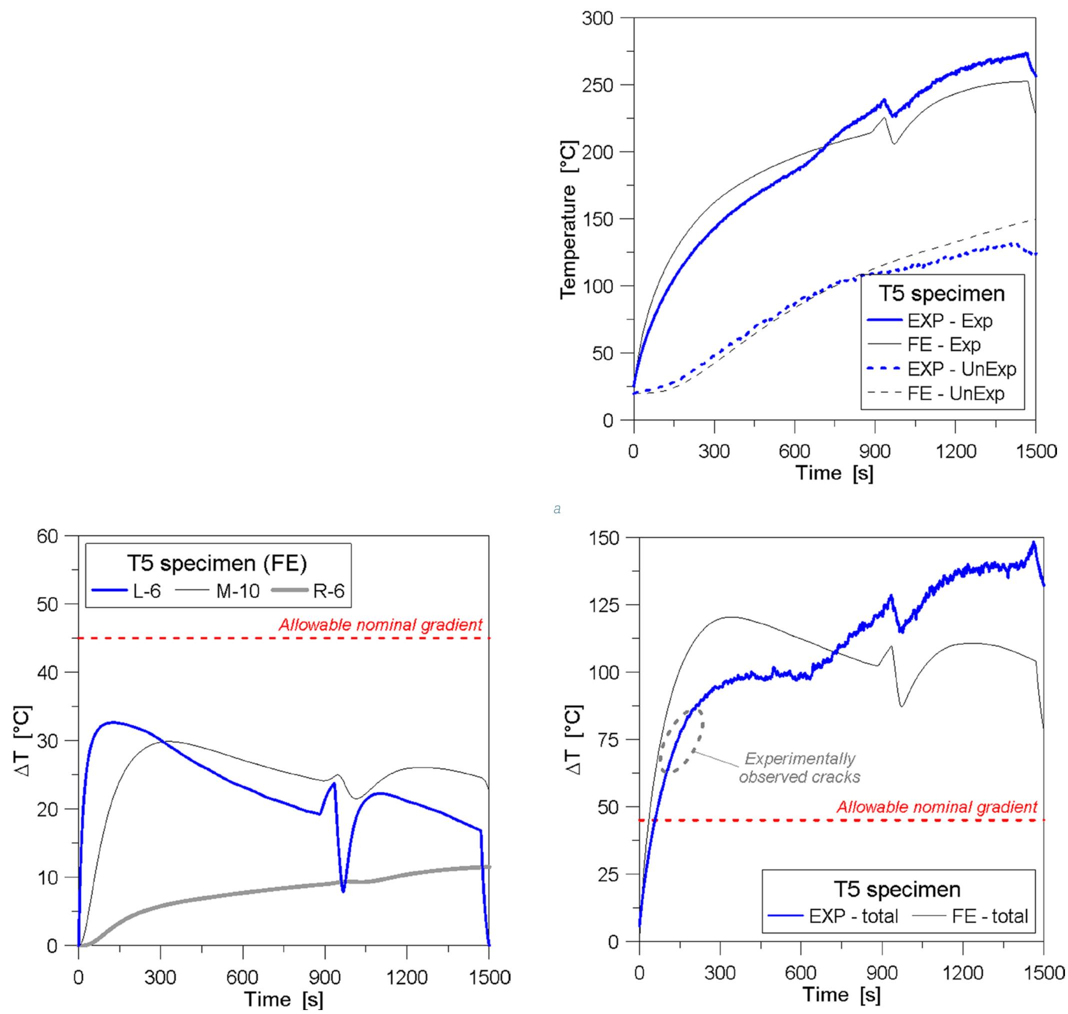


FIG. 8 Comparison between experimental and numerical (ABAQUS) results for the laminated T5 sample: (a) temperature history; (b) numerically calculated temperature gradient for all the laminate plies, as a function of time and; (c) absolute / total gradient for the T5 sample, as obtained from the test and the FE model

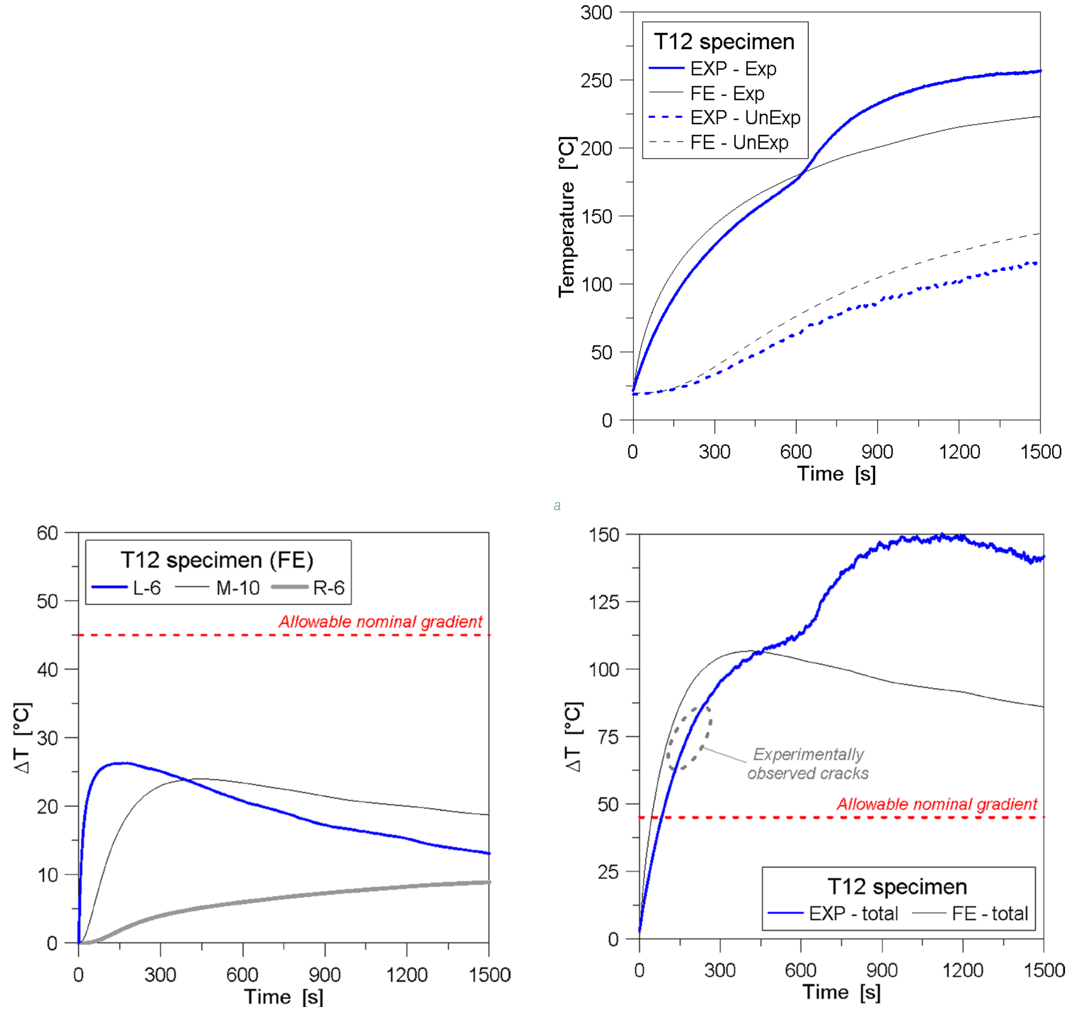
Additional comparative calculations were then carried out by taking into account the FE temperature gradient over time, through the thickness of the sample. Fig. 8(b) presents temperature gradients for each ply, as obtained from the T5 numerical simulation. At the time of the experimental investigation - for the laminated specimens - no additional thermocouples were mounted within the thickness of the given sandwich section, but only at the external faces of the samples. Consequently, no direct DT comparisons can be carried out for each glass ply, and the FE results in Fig. 8(b) can offer qualitative feedback only. As shown, the exposed surface ("L-6" plot) heats up the fastest, and an high temperature gradient (> 30°C) is predicted at an early stage of the simulations (≈130s).

The middle, 10mm thick glass ply ("M-10") shows a DT evolution in time of lower magnitude, due to the protective contribution of the exposed layer (≈ 30°C the maximum DT prediction), as well as a certain delay in the temperature increase (≈250s). The middle layer itself insulates the unexposed glass ply, which shows limited DT values (in the order of 50% the other plies, "R-6" plot) and a totally different evolution in time. In Fig. 8(b), the sudden drop of DT for the exposed L-6 ply can still be observed at approx. 950s of exposure, in accordance with the experimental findings. With regard to the examination of the middle and unexposed glass layers, mostly null effects can be perceived from the same heat flux drop.

For laminated glass systems (Table 2), the thermal fracture is conventionally ensured insofar as the allowable nominal gradient for the weakest ply is not exceeded, according to the existing recommendations. In the case of the T5 laminated assembly (as well as the T12 specimen discussed in the following chapters), the experimental crack was observed to initiate in the range of 230-260s of exposure. In this regard, the absolute/total gradient for the sample of investigation can offer some further feedback on its overall performance. In Fig. 8(c), the absolute variation is shown, over time, for the temperature measurements at the exposed and unexposed nodes (i.e. assuming a fully monolithic performance for the laminated cross-section). Compared to the reference nominal value of 45°C (Table 2), it can be observed that the experimental cracks were typically observed to propagate for absolute thermal gradients in the order of 60-70°C. The actual effect of the intermediate PVB foils for the nominal layered section (Fig. 7), however, requires further extended investigations.

In Fig. 9, finally, comparative results are shown for the T12 laminated specimen, having the same geometrical and mechanical properties of the T5 sample (Fig. 7). In accordance with earlier observations, a close agreement with the experiments was observed, especially for the early stage of the FE analysis (600-700s, with less than 10% of scatter). At approximately 600s of exposure, however, a marked increase of experimental temperatures for the exposed node can be observed. Such an effect can be justified, most probably, by the detachment of the aluminium foil shielding the thermocouple of interest from direct radiation. A mostly linear trend was, in fact, recorded for the heat flux (Fig. 3), thereby excluding possible abrupt variations in the loading condition. For the same reason, a mostly stable temperature increase was numerically predicted for the exposed node, hence resulting only in an apparent mismatch between the compared curves (15-20% their scatter at the final stage of the experiment). In the case of the unexposed node, similarly to the T5 specimen, the FE analysis generally overestimated the corresponding test data, with increasing scatter towards the final phase of thermal exposure (+30%, after 1500s of testing). The close correlation with T5 observations (Fig. 8(a)) can be considered as a suggestion for possible 1D modelling limitations, requiring the use of more refined FE models able to capture the actual performance of the laminated specimens.

With regard to the temperature gradient in each glass layer that were taken into account for the T12 assembly (Fig. 9(b)), a close qualitative correlation with the T5 numerical predictions can again be perceived. Some minor variations in Figs 8(b) and 9(b) are related to the different input thermal loading for the T5 and T12 samples (see Fig. 3). Accordingly, the exposed glass ply is subjected to > 25°C of thermal gradient in the first 150s of exposure. The middle glass layer suffers a lower and delayed DT increase (-15% the exposed ply, after 300s of thermal loading). The unexposed glass layer, finally, is mostly protected by the other assembly components. A maximum DT in the order of 10°C can be noticed only after 1500s of exposure.



b c

FIG. 9 Comparison between experimental and numerical (ABAQUS) results for the laminated T12 sample: (a) temperature history, (b) calculated temperature gradient for all the laminate plies, as a function of time and (c) absolute / total gradient for the T5 sample, as obtained from the test and the FE model

In Fig. 9(c), finally, a qualitative agreement can again be observed between the T12 and T5 fracture performance, insofar as the layered cross-section of Fig. 7 is roughly approximated to an equivalent, fully monolithic section. In this regard, further investigations are required to capture the contribution of common interlayer foils for the overall thermo-mechanical performance of glass laminates, both from a pure thermal point of view, as well as in terms of mechanical efficiency, given the limited resistance and shear stiffness of these films to high temperatures. The effect of simplified numerical approaches for laminated sections under radiant heating and fire, in particular, needs to be assessed in terms of experimental data.

4 SUMMARY AND CONCLUSIONS

In this paper, some selected results from a research collaboration between the involved authors were presented, as obtained during two Short-Term Scientific Missions (STSMs) approved and financially supported in Spring 2018 by the EU-COST Action TU1403 “Adaptive Façades Network”, as well as from the excellent networking activity that still follows the same STSMs. During the joint research project, special care was given to the development of a reliable thermo-mechanical model for monolithic and laminated structural glazing at elevated temperatures. Further studies would require the calibration of several input features, especially those being the key influencing parameters of both thermal and mechanical aspects of relevance on the overall structural performance of these systems.

As a first step, one-dimensional (1D) models were used to study the thermal behaviour through the cross-section of glass plies. The typical heat transfer FE analysis was validated against previous experimental investigations, where glass specimens with several geometrical and mechanical features have been exposed to radiant heating, resulting - in some cases - in breakage of the panels. Although the adopted FE modelling approach includes several simplifications - first of all the lumped thermal performance of the glass plates object of analysis - interesting conclusions can be drawn and used in the future developments of more refined thermo-mechanical models.

One major challenge in the FE assessment of the structural performance of glass systems under thermal loading is that the available information on the temperature dependence of various thermo-physical and mechanical material properties in the literature is scarce. Therefore, experimental testing is generally highly valuable. However, testing glass samples and assemblies at high temperatures is commonly challenging, time-consuming and costly. Furthermore, the measurements themselves can include difficulties and uncertainties (see for example Bedon et al. (2018a)). It requires careful planning to decide how the temperatures and heat fluxes are measured to obtain the relevant information for the validation of the numerical models.

In terms of numerical modelling, 1D assemblies are typically associated with a well-known computational efficiency, but also to marked simplifications in their input features and expected results. In this regard, compared to more detailed two-dimensional (2D) or three-dimensional (3D) numerical models, 1D systems are not able to account for several key aspects for thermo-mechanical simulations, such as:

- Thermal boundary effects (i.e. thermal exposure of the samples faces to the assigned thermal load)
- Mechanical boundary effects, namely represented by the temperature distribution and evolution in time, in the contact regions between the glass specimens and the supports (and/or the test setup components, etc., typically consisting of different materials with specific thermo-mechanical features)
- Size effects, being the 1D (and 2D) models intended to predict the temperature distribution in a given ideal section of the specimen under investigation, i.e. disregarding edge effects and other local phenomena

The sensitivity of similar 1D thermal models is then further emphasised insofar as the mechanical performance of the same systems is analysed under the effect of elevated temperatures. At the current stage, for example, the actual role and FE modelling assumptions for common interlayer foils used in laminated glass assemblies - from both a thermal and mechanical point of view - still requires further studies. These aspects are currently under investigation, as an extension of the ongoing research study.

Acknowledgements
The EU-COST Action TU1403 "Adaptive Façades Network" (2014-2018, http://www.tu1403.eu) is gratefully acknowledged for providing excellent research cooperation between the involved authors. Part of the research study discussed in this research paper has been financially supported by the EU-COST Action TU1403 in the form of Short-Term Scientific Mission grants for the involved authors (Dr. Kozłowski visiting University of Trieste, Italy, and Dr. Bedon visiting RISE, Sweden). In addition, COST is acknowledged for facilitating fruitful networking between the authors and international experts.

References

Aguilar, J.O., Xamán, J., Olazo-Gómez, Y., Hernández-López, I., Becerra, G., & Jaramillo, O.A. (2017). Thermal performance of a room with a double glazing window using glazing available in Mexican market. *Applied Thermal Engineering, 119*: pp.505-515

Aldawoud, A. (2017). Assessing the energy performance of modern glass façade systems. *MATEC Web of Conferences, 120,* paper id: 08001, doi: 10.1051/matecconf/201712008001

Baumgärtner, L., Krasovsky, R.A., Stopper, J., & von Grabe, J. (2017). Evaluation of a solar thermal glass façade with adjustable transparency in cold and hot climates. *Energy Procedia, 122*: pp.211-216

Bedon, C. (2017). Structural glass systems under fire: overview of design issues, experimental research, and developments. *Advances in Civil Engineering, Volume 2017*, Article ID 2120570, 18 pages. Retrieved from https://doi.org/10.1155/2017/2120570

Bedon, C., & Louter, C. (2018). Thermo-mechanical Numerical Modelling of Structural Glass under Fire - Preliminary Considerations and Comparisons. *Proceedings of Challenging Glass Conference, vol. 6*, pp. 513-524, https://doi.org/10.7480/cgc.6.2173

Bedon, C., Honfi, D., & Kozłowski, M. (2018a). Numerical Modelling of Structural Glass Elements under Thermal Exposure. *The 3rd International Electronic Conference on Materials Sciences*. DOI10.3390/ecms2018-05241

Bedon, C., Pascual Agullo, C., Luna-Navarro, A., Overend, M., & Favoino, F. (2018b). Thermo-mechanical Investigation of Novel GFRP-glass Sandwich Façade Components. *Proceedings of Challenging Glass Conference, vol. 6*, pp. 501-512, https://doi.org/10.7480/cgc.6.2172

Bedon, C., Zhang, X., Santos, F., Honfi, D., Kozlowski, M., Arrigoni, M., Figuli, M., & Lange, D. (2018c). Performance of structural glass façades under extreme loads – Design methods, existing research, current issues and trends. *Construction and Building Materials, 163*: pp.921-937

Cardenas, B., Leon, N., Pye, J., & Garcia, H.D. (2016). Design and modeling of high temperature solar thermal energy storage unit based on molten soda lime silica glass. *Solar Energy, 126.* pp.32–43

Cuzzillo, B.R, & Pagni, P.J. (1998). Thermal breakage of double-pane glazing by fire. *Journal of Fire Protection Engineering*, 9(1): 1-11

Debuyser, M., Sjöström, J., Lange, D., Honfi, D., Sonck, D., & Belis, J. (2017). Behaviour of monolithic and laminated glass exposed to radiant heating. *Construction and Building Materials, 130.* pp.212–229

Debuyser, M. (2015). *Exploratory investigation of the behaviour of structural glass in fire.* (Master's Dissertation) Ghent University, Belgium.

Feldmann, M., Kasper, R., Abeln, B., Cruz, P., Belis, J., Beyer, J., Colvin, J., & et al. (2014). Guidance for European Structural design of glass components – support to the implementation, harmonization and further development of the Eurocodes. In P. Dimova & D. Feldmann (Eds) *Report EUR 26439, Joint Research Centre-Institute for the Protection and Security of the Citizen*. doi: 10.2788/5523.

Fang, Y., Eames, P.C., & Norton, B. (2007). Effect of glass thickness on the thermal performance of evacuated glazing. *Solar Energy, 81(3)*. pp.395-404

Favoino, F., Jin, Q., & Overend, M. (2014). Towards an ideal adaptive glazed façade for office buildings. *Energy Procedia, 62*. pp.289-298

Ghosh, A., Norton, B., & Duffy, A. (2016). Measured thermal & daylight performance of an evacuated glazing using an outdoor test cell. *Applied Energy, 177* pp.196-203

Ghoshal, S., & Neogi, S. (2014). Advanced Glazing System - Energy Efficiency Approach for Buildings - A Review. *Energy Procedia, 54.* pp.352-358

Li, D., Li, Z., Zheng, Y., Liu, C., & Lu, L. (2015). Optical performance of single and double glazing units in the wavelength 337-900 nm. *Solar Energy, 122.* pp.1091-1099

Haldimann, M., Luible, A., & Overend, M. (2008). *Structural use of glass*. IABSE, ISBN 978-3-85748-119-2

Hasselaar, B., & Looman, R. (2007). The climate adaptive skin, the integral solution to the conflict between comfort and energy performance. *Proceedings of CIB World Building Congress 2017*, pp. 1115-1125

Miller, C., Thomas, D., Kämpf, J., & Schlueter, A. (2015). Long wave radiation exchange for urban scale modeling within a Co-simulation environment. *Proceedings of CISBAT 2015,* September 9-11, 2015, Lausanne, Switzerland, pp.871-876

Parra, J., Guardo, A., Egusquiza, E., & Alavedra, P. (2015). Thermal performance of ventilated double skin façades with Venetian blinds. *Energies,* 8: 1882-4898, doi: 10.3390/en8064882

prEN thstr:2004. (2004). *Glass in Buildings - thermal stress capitulation method,* CEN, Brussels, Belgium

Simulia. (2018). ABAQUS v. 6.14 computer software and online documentation, Dassault Systems, Providence, RI, USA

Stefanizzi, P., Wilson, A., & Pinney, A. (1990). Internal long-wave radiation exchange in buildings: Comparison of calculation methods: Review of Algorithms. *Building Services Engineering Research and Technology, 11(3)*: pp.81-85

Tong, T.W. (1994). *Thermal Conductivity 22.* Lancaster, PA, USA: Technomic Publishing Company, Ltd.,, ISBN 1-56676-172-7

Tong, S.T., Zhu, L.B., Guo, W., & Ma, F.D. (2002). Numerical simulation on thermal radiation of low emissivity glass surface. *Journal of Building Materials,* 5: pp.60-65

Tofilo, P., & Delichatsios, M. (2010). Thermally induced stresses in glazing systems. *Journal of Fire Protection Engineering*, 20(2): pp.101-116

Wang, T.-P., & Wang, L.-B. (2016). The effects of transparent long-wave radiation through glass on time lag and decrement factor of hollow double glazing. *Energy and Buildings*, 117. pp.33-43

Wang, T.-P., Wang, L.-B., & Li, B.-Q. (2013). A model of the long-wave radiation heat transfer through a glazing. *Energy and Buildings, 59* pp.50-61

What is an Adaptive Façade? Analysis of Recent Terms and Definitions from an International Perspective

Rosa Romano[1*], Laura Aelenei[2*], Daniel Aelenei[3*], Enrico Sergio Mazzucchelli[4]

* Corresponding author
1 Department of Architecture, University of Florence, rosa.romano@unifi.it
2 LNEG-National Energy and Geology Laboratory
3 Faculty of Science and Technology, Universidade Nova de Lisboa
4 Politecnico di Milano

Abstract

Adaptive façades can improve the building's energy efficiency and economics, through their capability to change their behaviour in real time according to indoor-outdoor parameters, by means of materials, components, and systems. Therefore, adaptive façades can make a significant and viable contribution to meeting the EU´s 2020 targets. Several different types of adaptive façade concepts have already been developed, and an increase in emerging, innovative solutions is expected in the near future. According to recent research, the word 'adaptive' in the context of building façades is often associated in the literature with a long list of similar words. Moreover, there is no consistent definition of façade adaptability, although studies exist in relation to characterisation issues, design parameter, and classification. Even within the discipline of architecture and engineering, words such as 'smart', 'intelligent', 'interactive', 'adaptive', or 'responsive' have been used loosely and interchangeably, creating confusion as to their specific meaning and their conceptual relationship to building performance and design. In response to this, the goal of this paper is to build a provisional lexicon, or descriptive, behavioural, and methodological words, to assist researchers and designers in navigating the field of high-performance façades that incorporate materially innovative and feedback-based systems. It offers a brief overview of current advances in this nascent and rapidly evolving field and articulates a broader conceptual territory for the word 'adaptive', used in many cases to describe the technological systems that interact with the environment and the user by reacting to external influences and adapting their behaviour and functionality. The objective of this paper is to contribute to these developments by presenting the findings. Furthermore, common definitions will be proposed, based on the characterisation design parameters, classification approaches, and real case studies.

Keywords

adaptive façade, energy efficiency, comfort, passive design, intelligent buildings, sustainable architecture

DOI 10.7480/jfde.2018.3.2478

1 INTRODUCTION

The need to comply with European regulations on the energy efficiency of new and existing buildings has led the construction and scientific research areas, in recent decades, to experiment within the sector of smart and adaptive envelopes: a new generation of vertical closure systems aimed at reducing to zero the net energy consumption of the buildings in which they are integrated, with the aim of improving the comfort and the sustainability of our cities (Davis, 1981; Wigginton & Harris, 2002).

As a matter of fact, over the same period, envelope systems have been transformed from passive technological solutions to active systems that are able to produce energy from renewable sources and, above all, are able to change a building in a dynamic and adaptive system, in terms of spatial configurations and behaviour of its external skin, to improve indoor comfort conditions. Thanks to the presence of smart materials and automated systems with different degrees of complexity, the building thereby becomes a dynamic system that can be compared to a living organism, in which each part reacts to external and internal stimuli, adapting to the surrounding context in order to regulate and optimise the overall energy balance necessary for its functioning.

To the traditional three typologies of building envelopes – conservative, selective, and regenerative – identified by Banham in 1969, a fourth typology has been added: the smart or adaptive envelope. Adaptive envelopes can actively control energy fluxes between indoor and outdoor. Moreover, they can adapt their properties to maximise indoor comfort and reduce energy consumption. Furthermore, several different types of adaptive envelope concepts have already been developed, and an increase in emerging, innovative solutions is expected in the near future. Adaptive façades, in fact, can ensure improvements in building energy efficiency and economics, through their ability to change their performance and behaviour in real time, according to indoor-outdoor parameters, by means of materials, components, and systems. Therefore, they can make a significant and viable contribution to meeting the EU´s 2020 targets.

Today's envelopes are predominantly passive systems and are largely exhausted from an energetic point of view. They can neither adapt to changing environmental conditions related to daily and annual cycles nor to changing user requirements. Multifunctional, adaptive, and dynamic façades can be considered the next big milestone in façade technology. Adaptive building envelopes are able to interact with the environment and the user by reacting to external output and adapting their behaviour and functionality accordingly: the building envelope insulates only when necessary, it produces energy when possible, and it shades or ventilates when the indoor comfort so demands (Aelenei, Brzezicki, Knaack, Luible, Perino, & Wellershoff, 2015).

Moreover, there is no consistent definition of façade adaptability, although studies related to characterisation issues, design parameters, and classification already exist. Even within the discipline of architecture and engineering, terms such as *'smart', 'intelligent', 'interactive', 'adaptive', or 'responsive'* have been used loosely and interchangeably, creating confusion as to their specific meaning and their conceptual relationship to building performance and design. In response to this, the goal of this paper is to build a provisional lexicon, *or descriptive, behavioural, and methodological words*, to assist researchers and designers in navigating the field of high-performance façades that incorporate materially innovative and feedback-based systems. The paper offers a brief overview of current advances in this rapidly evolving field and articulates a broader conceptual territory for the word 'adaptive', used in many cases to describe the technological systems that are able to interact with the environment and the user by reacting to external influences and, in turn, adapting their behaviour and functionality. Finally, the objective of this paper is to contribute to these developments by presenting the findings. Furthermore, common definitions will be proposed, based on the characterisation design parameters, classification approaches, and real case studies.

2 'ADAPTIVE' DEFINITIONS

Most of definitions of a building envelope establish it as an enclosure, a separation between the indoor and outdoor environment that provides the following functions: support, control, finish (aesthetics), and distribution of service. However, we are more interested in the building envelope, without distinction between wall and roof, as an interface and not a separation, between exterior environmental factors and interior demands of the occupants. The building envelope can be considered, in fact, as an environmental moderator (López, Rubio, Martín, & Croxford, 2017).

For years, architects and building scientists have imagined the possibility that future buildings would possess envelopes that replicate our skin's adaptive response to changing environmental conditions. In his 1969 essay, 'A Home is not a House', Banham (1969) introduced minimal environmental solutions such as the tent and the campfire as representations of a building capable of dynamically modifying its boundaries and thermal properties in response to the environment. In 1976, Negroponte explained the concept of a responsive environment, capable of playing an active role, initiating to a greater or lesser degree changes as a result and function of complex or simple computations (Negroponte,1976). In 1981, Mike Davies proposed the idea of 'The polyvalent wall': an envelope system in which several functions are integrated into one layer (Davies, 1981). Another means of categorising responsive architecture is, in terms of rates of change, the approach promoted by Stuart Brand (1995) in his book 'How Buildings Learn'. Brand's 'Shearing layers of change' diagram, with its concentric rings of building components organised according the irrelative rates of change, promoted the idea that building components should be separated according to their rate of change.

However, it is only in recent years that technological research has investigated new experimentation frontiers capable of reaffirming the osmotic quality of a process of exchange concerning energy flows that have been passed and exchanged right through the envelope (Altomonte, 2008). In this regard, there is new research to demonstrate whether the vertical closure surface can be equipped with systems designed to ensure a dynamism that allows them to control the energy flows in the same way as a biological organism does. From the shading device system of the Arab World Institute in Paris by Jean Nouvel to the dynamic screenings of Al Bahar Towers in Abu Dabi by Aedas Architects, the new frontiers of experimentation in architecture are oriented towards proposing new models of living in which the building organism is also able to autonomously ensure the comfort of its users. In this way, the evolution and dissemination of IT (Information Technology) control systems (from home automation to Building Management Systems) to transfer the potential of systems equipped with artificial intelligence to the building scale, have also ensured the regulation of space in the absence of human users and in relation to a whole series of requirements that guarantee an optimisation from the functional and physical perspective of the built space.

However, what does 'adaptive façade' really mean? Is it possible to find a single definition for the complex panorama of smart envelope systems that have characterised the last decade's contemporary architecture?

From the point of view of the biological scientists: 'adaptation' can be defined as the evolutionary process whereby an organism becomes better able to live in its habitat (Dobzhansky, Hecht, & Steere, 1968). According to recent research in the field of architecture, the term 'adaptive' in the context of building façades is often associated in the literature with a long list of similar terms: active (Ochoa & Capeluto, 2008); accommodating; adaptable (Frei, 2015; Möller & Nungesser 2015; De Marco Werner, 2013); adjustable; advanced (Ad, Heiselberg & Perino, 2011); biomimetic (Vermillion, 2002); bio-inspired (Loonen, 2015); controllable (Konstantoglou, Kontadakis, & Tsangrassoulis, 2013); kinetic (Fortmeyer & Linn, 2014; Loonen, 2010; Ramzy & Fayed, 2011; Fox & Yeh, 1999; Wang, Beltrán, & Kim, 2012); intelligent (Knaack & Klein, 2008; Velikov & Thün, 2013; Kroner, 1997; Clements & Croome, 2004; Hayes-Roth, 1995; Wigginton & Harris, 2002; Compagno, 2002; Masri, 2015); interactive (Velikov & Thün, 2013); living; modifying; movable (Schumacher, Schaeffer, & Voght, 2010); polyvalent (Davies, 1981); reactive; reconfigurable; reflexive; resilient; responsive (Velikov & Thün, 2013; Negroponte, 1975; Heiselberg, Inger, & Perino, 2012; Kolodziej & Rak, 2013; Meagher, 2015; Ferguson, Siddiqi, Lewis, & De Weck, 2007); selective; sensitive; sentient; smart (Velikov & Thün, 2013; Fox & Yeh, 1999; Brugnaro, Caini, & Paparella, 2014); switchable (Beevor, 2010); transformable; transient; and passive.

3 REVIEW OF EXISTING DEFINITIONS OF ADAPTIVE FAÇADES

Adaptable architecture is described for the first time by Frei Otto as a system that is able to change of shape, location, utilisation, or spaciousness. By change of location, he wants to indicate that the technological system is mobile, easily transportable, and able to be constructed and deconstructed quickly. The basic principle that is used for the construction of adaptable architecture is the 'Lightweight Principle' that relies on the optimal use of material and built mass (Möller & Nungesser, 2015).

Adaptive façades, in particular, consist of multifunctional, highly adaptive systems, in which the physical separator between the interior and exterior space is able to change its functions, features, or behaviour over time in response to transient performance requirements and boundary conditions, with the aim of improving the overall building performances (Loonen et al. 2015). Furthermore, these types of façade allow energy to be saved by adapting to prevailing weather conditions, and support comfort levels by immediately responding to occupants' needs and preferences (Loonen, Trčka, Cóstola, & Hensen, 2013). Consequently, adaptability can be understood as the ability of a system to deliver intended functionality, considering multiple criteria under variable conditions, through the design variables changing their physical values over time (Ferguson et al., 2007).

In accordance with the above semantic frame, adaptive façades should provide an adequate response to changes in the internal and external environments to ensure or improve the functional requirements of the envelopes in terms of heat, air and water vapour flow, rain penetration, solar radiation, noise, fire, strength and stability, and aesthetics. Therefore, multi-functional adaptive façades should be able to respond repeatedly and reversibly over time to changes in performance requirements and changing boundary conditions. In other words, adaptive façades should be able to provide controllable insulation and thermal mass, radiant heat exchange, ventilation, energy harvesting, daylighting, solar shading, or humidity control (Aelenei, Aelenei, & Pacheco Vieira, 2016).

Moreover, in the context of the smart cities, where the buildings must be interactive in the zero energy frame to provide the operational flexibility needed to avoid or reduce the mismatching, these innovative envelope systems can play a key role (Aelenei et al., 2016). The concept of the smart building is, in fact, closely linked to that of the adaptive façade, as the façade itself is the main element capable of changing its structure to ensure the required performances, emphasising its resemblance to human skin. The envelope thereby becomes a real organic system connected to the building's central control system and to the air conditioning system, which can be compared with the human artery system (Romano, 2011).

For this reason, the adaptive façades built in recent years in many geographical areas are characterised by the complementary nature of the system and building technologies, and by the presence of regulation and control systems that make them a key element in the complex building-plant system.


a


b

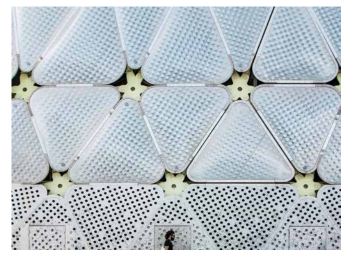

c

FIG. 1 Some pictures of active façades: a) ARTICULATED CLOUD, Pittsburgh (USA), 2004; b) Nordic Embassies in Berlin, Berlin (DE), 1999; c) MEDIA-TIC, Barcelona (SP), 2007

3.1 ACTIVE FAÇADES

Active façades (Figs. 1a), b) and c)) can be definite technological systems which have integrated elements through which envelopes self-adjust to changes initiated by the internal or external building environments, achieving comfort conditions while minimising energy consumptions. These active features should be both automatic and manual and should not need to include sophisticated electronics (Ochoa & Capeluto, 2008).

3.2 ADVANCED FAÇADES

An advanced façade is the outer, weather-protecting layer of a building that can contribute to heating, cooling, ventilation, and lighting requirements and can promote interior comfort through efficient, energy saving measures. The main difference between advanced envelope concepts and other energy efficient envelope concepts is the application of responsive building elements and their integration with building services systems and energy systems in combination with advanced control (Ad et al., 2011).

3.3 BIOMIMETIC OR BIO-INSPIRED FAÇADES

The skins of plants and humans tend to be seen as the most straightforward emulation model and inspiration source for multifunctional and truly sustainable enclosure systems. Functional bio-inspiration can either be direct or indirect. The first approach directly copies the observed functional principle into a building envelope technology that performs the same role. This is an example of phototropism (i.e. changing in response to light) and heliotropism (i.e. changing in response to the sun), applied, for example, in the climate adaptive building shells concepts that enable the active collection or rejection of solar energy (Vermillion, 2002). The indirect approach is loosely based on a selected biological principle but requires an intermediate abstraction step in its translation from biological principle to building envelope technology (Loonen et al., 2015) (Figs. 2a), b) and c)).

a *b* *c*

FIG. 2 Some pictures of bio-inspired façades: a) Hygroscope, Centre Pompidou, Paris (FR), 2012; b) BIPV Adaptive Flakes, Milan (IT), 2017; c) BIQ – The Algaehouse – The Clever Treefrog, Hamburg (DE), 2013

a *b* *c*

FIG. 3 Some pictures of kinetic façades: a) Campus Kolding, Kolding (Denmark), 2014; b) Kiefer Technic Showroom, Bad Gleichenberg (A), 2007; c) ThyssenKrupp Quarter, Essen (DE), 2010

3.4 KINETIC FAÇADES

In 1970, Zuk and Clark defined kinetic architecture as an architectural form that can be inherently displaceable, deformable, expandable, or capable of movement (De Marco Werner, 2013). To elaborate, a kinetic façade is a technological system in which there is a certain kind of motion (Loonen, 2010) and that is able to guarantee variable locations or mobility and/or variable geometry to all or one of its parts. (Fox & Yeh, 1999). The term ‘kinetic’ also indicates an organism’s response to a particular kind of stimulus in biology (Wang et al., 2012) and an ability to modulate energy in its primary forms: visible light and heat. A kinetic façade (Figs. 3a), b) and c)) can respond to the flow energy, both natural and man-made, that primarily affects building performance and the comfort of the people in them (Fortmeyer & Linn, 2014). These types of envelope, in general, need to be efficiently tuned to boundary conditions such as climatic conditions, different locations, varying functional requirements, or emergency situations. In order to guarantee the kinematic, an actuation force is needed that generates the movement.

3.5 INTELLIGENT FAÇADES

Intelligent buildings are those which combine both active and passive intelligence - active features and passive design strategies - to provide maximum occupant comfort using minimum energy (Kroner, 1997). In this context, the definition of 'intelligent' façade introduces the idea of dynamic movement and the 'component' façade in which all building services components are integrated (Knaack & Klein, 2008). Furthermore, the term 'intelligent', when applied to a façade, must indicate the responsive ability of the façade to change according to environmental conditions (Compagno, 2002). The intelligent skin is therefore a composition of elements, which acts as a barrier to the outside environment, yet can respond to climatic changes through the automatic reconfiguration of its systems (Masri, 2015) to produce a pleasant indoor environment (Clements-Croome, 2004). The primary functions that must be performed by intelligent systems were considered: perception, reasoning, and action. This corresponds in robotics to sensors, control processors, and actuators (Hayes-Roth, 1995). For these reasons, an intelligent façade should be able to change itself through 'instinctive autonomic adjustment' (Wigginton & Harris, 2002), optimising the building's systems relative to climate, energy balance, and human comfort, typically based on predictive models. This is often accomplished through building automation and physically adaptive elements such as louvres, sunshades, operable vents, or smart material assemblies (Velikov & Thün, 2013).

3.6 INTERACTIVE FAÇADES

a b c

FIG. 4 Some pictures of interactive façades: a) GreenPix – Zero Energy Media Wall, Beijing (cn), 2018; b) SolPix, New York (US), 2010; c) Cyclebowl, Hannover Expo (DE), 2000

The term 'interactive' is used less frequently with regard to building envelopes than in reference to computer-enabled artworks, installations, and other such environments that encourage active public participation. However, an interactive façade (Figs. 4a), b) and c)) requires human input to initiate a response, and it may also be equipped with sensors and an automated building management system and programmed to optimise energy conservation while simultaneously ensuring the comfort of its inhabitants (Velikov & Thün, 2013).

3.7 MOVABLE FAÇADES

Movable façades can be defined as technological systems that are able to rapidly adapt to the environmental conditions and location, as well as being defined by the opening elements themselves. Furthermore, where individual parts of flexible enclosures are equipped with photovoltaic elements that track and follow the position of the sun, these type of envelope systems can produce renewable energy, thereby reducing the energy consumption of new or existing buildings (Schumacher, Schaeffer, & Voght, 2010).

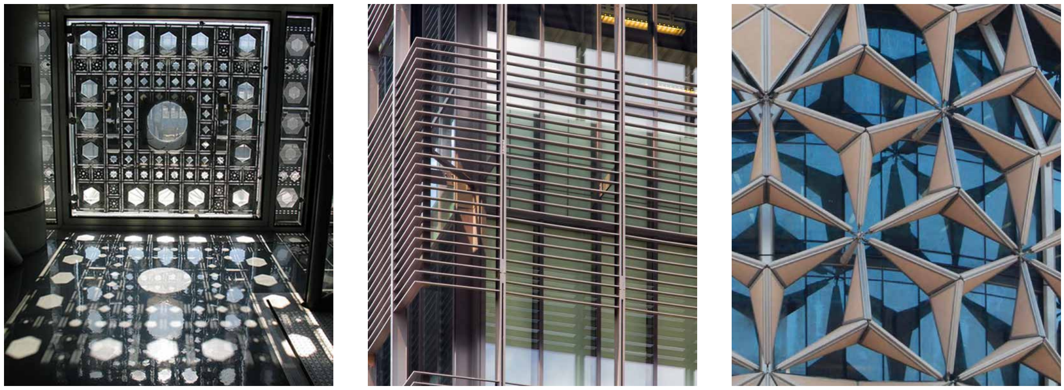
3.8 RESPONSIVE FAÇADES

Functional responsiveness in contemporary architecture can be defined as a system's ability to adapt itself to deliver intended functionality under varying conditions through the design variables that change their physical values (Ferguson et al., 2007). A responsive façade takes an active role, initiating changes, to a greater or lesser degree, as a result and function of complex or simple computations (Negroponte, 1975).

Meagher (2015) defines responsive components as all those elements of the building that adapt to the needs of people as well as to changes in the environment. These components may be high tech systems that employ sensor networks and actuators to monitor the environment and automate control of operable building elements. He also uses this term to refer to the moveable, operable, often manually controlled elements of buildings which allow the adjustment of the building envelope and interior in order to adapt the building's performance to meet everyday needs. Furthermore, these technological systems can be actively used for transfer and storage of heat, light, water, and air. They assist in maintaining an appropriate balance between optimum interior conditions and energy performance by reacting in a controlled and holistic manner to outdoor and indoor environment changes and to occupants' requirements. Responsive building elements can be essential technologies for the exploitation of environmental and renewable energy resources, and in the development of integrated building concepts (Heiselberg et al., 2012).

In other words, responsive building envelopes (Figs. 5a), b) and c)) can be defined as technological systems in which external environmental conditions (e.g. ventilation, humidity, light volume, radiation, and temperature) influence the interior parameters of the building (i.e. thermal and light comfort). The most common solutions are based on several specialised subsystems (such as structural elements, sensors, mechanical actuators, membranes, control devices, etc.) that are responsible for changing the envelope's geometry according to stimulus and programmed performance (Kolodziej & Rak, 2013).

A responsive building skin includes, in fact, functionalities and performance characteristics similar to those of an 'intelligent' building skin, including real-time sensing, kinetic climate-adaptive elements, smart materials, automation, and the ability for user override. However, it also includes interactive characteristics such as computational algorithms that allow the building system to self-adjust and learn over time, as well as the ability for inhabitants to physically manipulate elements of the building envelope to control environmental conditions (Velikov & Thün, 2013).



a b c

FIG. 5 Some pictures of responsive façades: a) Arab World Institute, Paris (FR), 1987; b) Yale Sculpture Building, New Haven Connecticut (USA), 2007; c) Al Bahar Towers, Abu Dhabi (AE), 2012

3.9 SMART FAÇADES

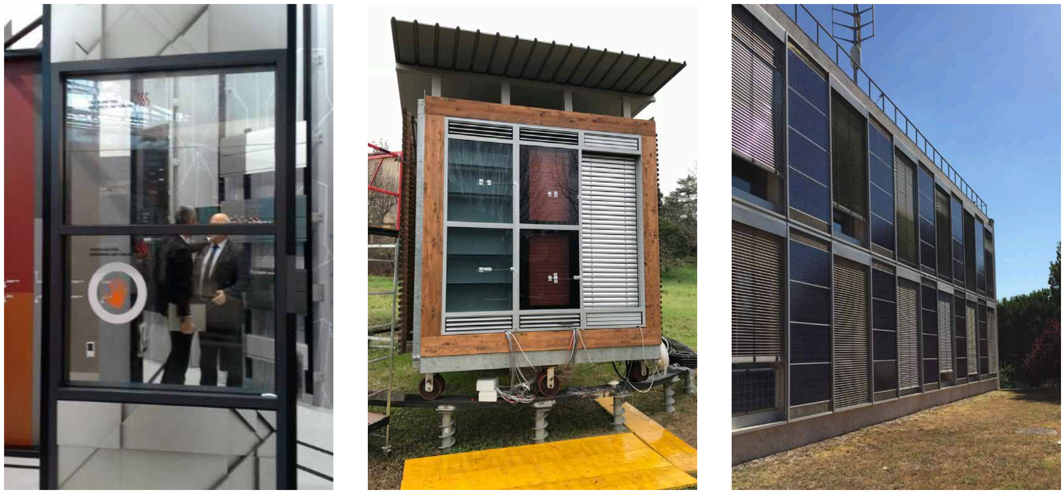
Within the design disciplines, the term 'smart' has most frequently been used in reference to materials and surfaces. Smart surfaces and materials show properties that are changeable and thus responsive to transient needs (Fox & Yeh, 1999); furthermore, they can play a significant role in intelligent, adaptive, and responsive envelopes because of these intrinsic properties. Examples of smart materials used in high-performance building skins include: aerogel – the synthetic low-density translucent material used in window glazing, phase-changing materials such as micro-encapsulated wax, salt hydrates, thermochromic polymer films, and building integrated photovoltaics (Velikov & Thün, 2013). Smart skin systems (Figs. 6a), b) and c)) are able to modify their physical-geometric characteristics to conform to changes in their environment by use of, for example, dynamic solar screenings, placed as a second skin on new and existing multilevel buildings. They also assume a fundamental role in the formal and characteristic aspects of the façade (Brugnaro, Caini, & Paparella, 2014).

3.10 SWITCHABLE FAÇADES

Switchable façades are built as transparent façades in which 'smart glasses' or, more generally, smart adaptive materials, are integrated to regulate light and energy flows through glass façades (Beevor, 2010).

3.11 TRANSFORMABLE FAÇADES

The response of transformable façades needs to be efficiently tuned to boundary conditions such as climatic conditions, different locations, varying functional requirements, or emergency situations. For this response, an actuation force is needed that generates movement. The transformation process goes from a compact to an expanded configuration or vice versa. The transformation phase must consist of controlled, stable movements and results in a rigid and secure structure, once it is locked in place (Chloë, 2016).



a b c

FIG. 6 Some pictures of smart façades: a) InDeWaG, Bayreuth (De), 2015; b) SELFIE Façade, Florence (I), 2017; c) Solar XXI – BIPV/T Systems, LISBON (P), 2006

4 CHARACTERISATION PARAMETERS OF ADAPTIVE FAÇADES (AFS)

As is demonstrated in the previous definitions, adaptive façade systems are notable for the presence of one or more of the following technological features:

- High-performance innovative materials and systems for absorbing and storing solar energy (e.g. smart, biomimetic, or bio-inspired façades, etc.);
- Devices for managing natural ventilation in combination with mechanical ventilation systems (e.g. adaptable, advanced, responsive façades, etc.);
- Mobile screens for controlling solar radiation (e.g., smart, adaptable, responsive, and switchable façades, etc.);
- Technological solutions designed to increase and/or control comfort inside the building (e.g. adaptable, active, kinetic, intelligent, interactive, and switchable façades, etc.);
- Building automation systems for the management of plants and elements of the building skin (e.g. intelligent, responsive façades, etc.).

These adaptive façade systems efficiently contribute to the energy balance of the building, limiting the need to use air conditioning devices, with a consequent reduction in energy consumption. In many cases, intrinsic dynamic façade systems are used, which delegate the adaptive capacity to the smart materials (e.g. PCM, TIM, ETFE, BIPV, etc.) of which they are composed. This is the case for the façade systems in which the adaptivity does not necessarily involve a change in the spatial configuration but rather concerns the regulation of the thermo-physical properties based on the external climatic conditions (e.g. switchable, smart, and biomimetic façades, etc.). In other cases, adaptivity (e.g. movable, responsive, and active façades, etc.) can be interpreted as the capacity to produce energy in a dynamic way, according to the energy requirement of the building.

In addition, the adaptivity is instead explicit in the façade system's capacity to move all or some of its parts. These are known as kinetic façade systems (Fox & Yeh, 1995; Wang et al. 2012) capable of changing by moving in space and taking on different structures and configurations over time. The long-term changes are achieved through reversible and unique conversions in the context of a flexible structure, while short-term reversible adaptations can be brought about through mechanical solutions.

5 CONCLUSION

The review of the definitions of adaptive façades shows that the architectural research on dynamic envelopes is moving towards innovative solutions. By exploiting the possibility of integrating IT systems, mechanical actuators, and innovative materials, these technological solutions are able to transform the envelope from a static element into a dynamic element capable of rapidly and efficiently changing shape in relation to specific functional, static, and physical requirements. The advanced screen, eco-efficient, and sustainable envelope interacts and regulates energy flows and, in some cases, becomes a plant system, by itself, capable of producing energy, heat, or electricity, and of distributing it at a building or even at an urban scale.

Adaptive architectures can therefore be considered as the last goal of contemporary architectural and technological research and they are always increasingly connected to the wish to propose new dynamic envelope models which – thanks to the presence of sensors, and system components for energy production as well as smart materials – help to reduce the building's energy requirement. These technological solutions, as previously mentioned, can control energy flows by regulating fixed devices that can be characterised by the presence of smart materials, variable structures (e.g. sunshades, opening/closing of windows, ventilation outlets, among others), manual or automatic control, or regulation in relation to the type of user and complexity of the building. This envelope typology is marked by dynamic anisotropy that is the capacity to offer different solutions for the different exposures of the building, where a change in the structure modulates the various environmental flows according to the climatic conditions of the place, including external climatic-environmental conditions. Therefore, it shows all those components that increase its capacity to change the structure in relation to the need to regulate the thermal, light, and sound energy flows passing through it (Banham, 1969).

Acknowledgements
The authors would like to gratefully acknowledge COST Action TU1403 "Adaptive Façades Network" for providing excellent research networking.

References
Ad, Aa. van der, Heiselberg, P., & Perino, M. (2011). *Designing with responsive buildings elements. IEA - ECBCS Annex 44.* Aalborg University

Aelenei, D., Aelenei, L., & Pacheco Vieira, C. (2016). Adaptive Façade: concept, applications, research questions. SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry, *Energy Procedia,* 91, pp.269-275.

Aelenei, L., Brzezicki, M., Knaack U., Luible, A., Perino, M., & Wellershoff, F. (2015). COST Action TU1403 - Adaptive Facades Network. In: Aelenei, L., Brzezicki, M., Knaack U., Luible, A., Perino, M., & Wellershoff, F., *Adaptive façade network — Europe.* Delft: TU Delft Open

Altomonte, S. (2004). *L'involucro architettonico come interfaccia dinamica: strumenti e criteri operativi per un involucro architettonico bioclimatico e sostenibile.* [The architectural envelope as a dynamic interface. Tools and criteria for sustainable architecture]. Florence: Editrice Alinea.

Banham, R. (1969). *The Architecture of the Well-Tempered Environment.* London: Architectural Press.

Brand, S. (1995). *How buildings learn: what happens after they're built.* London: Penguin (Non Classics).

Brugnaro, G., Caini, M., & Paparella, R. (2014). Energy saving through Building Envelope Innovation: Smart Skin Design. Recent Advances in Urban Planning. *Sustainable Development and Green Energy,* pp.35-44.

Beevor, M. (2010). *Smart Building Envelopes*. (4th Year Project Report). University of Cambridge, Department of Engineering.

Chloë, M. (2016). *Structural Adaptive Façades.* (Master's Dissertation).Ghent University, Ghent.

Clements- Croome, D.J.. (2004). Building environment, architecture and people. In Clements-Croome, D.J. (ed.) *Intelligent buildings: Design, Management and Operation.* pp.53-100. London: Thomas Telford.

Compagno, A. (2002). *Intelligente Glasfassaden: Material, Anwendung, Gestaltung* [Intelligent Glass Façades: Material, Practice, Design]. Birkhäuser Verlag

Davis, M. (1981). A Wall for all Seasons. *RIBA Journal, 88*

De Marco Werner, C. (2013). *Transformable and transportable architecture: analysis of buildings components and strategies for project design* (Master's thesis). Escuela Técnica Superior de Arquitectura de Barcelona. Barcelona

Dobzhansky, T., (1968). On some fundamental concepts of evolutionary biology. In Dobzhansky, T., Hecht, M.K., & Steere, W.C., *Evolutionary Biology, 2.* pp. 1-34. New York: Appleton-Century-Crofts.

Ferguson, S., Siddiqi, A., Lewis, K., & De Weck, O. (2007). Flexible and reconfigurable systems: Nomenclature and review. *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Las Vegas, Nevada, USA, pp. 249-263.

Fortmeyer, R., & Linn, C. D. (2014). *Kinetic Architecture: design for Active Envelope.* Australia: The Images Publishing Group Pty Ltd.

Fox, M.A., Yeh, B.P. (1999). Intelligent kinetic systems in architecture. *Managing Interactions in Smart Environments,* pp.91-103.

Knaack, U., & Klein, T. (2008). *The Future Envelope 1: A Multidisciplinary Approach.* Amsterdam: IOS Press.

Kolodziej, P., & Rak, J. (2013). Responsive building envelope as a material system of autonomous agent. *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia*, pp.945-954.

Konstantoglou, M., Kontadakis, A., & Tsangrassoulis, A. (2013). Dynamic Building Skins: Performance Criteria Integration. *PLEA2013 - 29th Conference, Sustainable Architecture for a Renewable Future,* Munich.

Kroner, W. M. (1997). An intelligent and responsive architecture. *Automation in Construction,* 6, pp. 381-393.

Hayes-Roth, B. (1995). An architecture for adaptive intelligent systems. *Artificial Intelligence, 72* (1–2), pp.329-365.

Heiselberg, P., Inger, A., & Perino, M. (2012). Integrating Environmentally Responsive Elements in Buildings. *Proceedings of the 27th AIVC Conference, Lyon.*

Loonen, R.C.G.M. (2014). Bio-inspired Adaptive Building Skins. *Biotechnologies and Biomimetics for Civil Engineering,* pp.115-134.

Loonen, R.C.G.M. (2010). *Climate Adaptive Building Shells What can we simulate?* (Master's Dissertation). Eindhoven University of Technology. Eindhoven

Loonen, R.C.G.M., Trčka, M., Cóstola, D., & Hensen, J.L.M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews, Vol. 25*, pp.483-493.

Loonen, R.C.G.M., Rico-Martinez, J.M., Favoino, F., Brzezicki, M., Menezo, C., La Ferla, G., & Aelenei, L. (2015). Design for façade adaptability – Towards a unified and systematic characterization. *Proceedings of the 10th Conference on Advanced Building Skins, Bern, Switzerland,* pp.1284-1294.

López, M., Rubio, R., Martín, S., & Croxford, B. (2017). How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes. *Renewable and Sustainable Energy Reviews, 67*, pp.692-703.

Masri, Y. (2015). Intelligent Building Envelopes: Design and Applications. *Proceedings of the International Conference on Building Envelope Design and Technology, Graz Advanced Building Skins 2015,* pp.37-46.

Meagher, M. (2015). Designing for change: The poetic potential of responsive architecture. *Frontiers of architectural Research, 4*, pp.159-165.

Möller, E., & Nungesser, H. (2015). Adaptable Architecture by Frei Otto: a case study on the future viability of his visions and some forward ideas. *Proceedings of the International Association for Shell and Spatial Structures, Amsterdam.*

Negroponte, N. (1976). Soft Architecture Machines. *Cambridge: MIT Press*

Ochoa, C.E., & Capeluto, I.G. (2008). Strategic decision-making for intelligent buildings: Comparative impact of passive design strategies and active features in a hot climate. *Building and Environment, 43* (11), pp.1829-1839.

Ramzy, N., & Fayed, H. (2011). Kinetic systems in architecture: New approach for environmental control systems and context-sensitive buildings. *Sustainable Cities and Society, 1 (3)*, pp.170-177.

Romano, R. (2011). *Smart Skin Envelope. Integrazione architettonica di tecnologie dinamiche e innovative per il risparmio energetico.* [Smart skin Envelope. Architectural integration of dynamic and innovative technologies for building energy saving]. Florence: Florence University Press

Schumacher, M., Schaeffer, O., & Voght, M. M. (2010*). Move. Architecture in Motion – Dynamic Components and Elements*. Basel: Birkhauser.

Velikov, K., & Thün, G. (2013). Responsive Building Envelopes: Characteristics and evolving paradigms. In: Trubiano, F., *Design and Construction of High Performance Homes.* pp. 75-92. London and New York: Routledge.

Vermillion, J. (2002). *Phototropic architecture: intelligent responses to sunlight stimuli. A new school of architecture for Ogerlthorpe University. Atlanta*. (Master's Thesis). Ball State University. Muncie, IN.

Wang, J., Beltrán, L., & Kim J. (2012). From Static to Kinetic: A Review of Acclimated Kinetic Building Envelopes. *Proceedings of The Solar Conference, 5*, pp. 4022-2029.

Wigginton, M., & Harris, J. (2002). *Intelligent Skins.* Oxford: Architectural Press.

A Redesign Procedure to Manufacture Adaptive Façades with Standard Products

Bahar Basarir[1*], M. Cem Altun[2]

* Corresponding author
1 Graduate School of Science Engineering and Technology, Istanbul Technical University, Turkey, baharbasarir@gmail.com
2 Department of Architecture, Istanbul Technical University, Turkey

Abstract

Although their potential for high environmental performance is largely accepted, adaptive façades have not yet become widespread in practice. Most of the current examples are developed by engineer-to-order design processes, as project-oriented, custom, and complex solutions. More simple and reliable solutions are needed to support the reuse of technical solutions between projects and increase the feasibility of adaptive façades. Therefore, this research aims to develop a procedure to design adaptive façades whose parts are based on engineered standard products with the least number of parts and layers. The research is initiated through the generation of concepts for designing adaptive façades to be manufactured using standard products. From several concepts, 'redesigning dynamic adaptive façades' has been selected for further investigation, as it pursues the goals for a solution determined for this research. A preliminary case study is conducted to redesign an adaptive façade to be manufactured with standard products. Its process steps are captured and analysed, and the steps that need improvement are revealed. To systematise and improve the captured redesign process, façade design and product design methodologies are analysed in the context of adaptive façade design. Redesign and reverse engineering processes used in product design are adapted and merged with façade and adaptive façade design processes, and a 5-phase adaptive façade redesign procedure is outlined. Each phase is developed based on mature tools and methods used in product and façade design. An iterative loop of development, application test, and review process is carried out for development of the process steps. Thus, a redesign procedure is generated by the combined application of DFMA and TRIZ in the synthesis of reverse engineering and redesign processes. Consequently, the application of the redesign procedure is demonstrated through a case study. The case study revealed that the procedure has the ability to generate a façade redesign that has a higher constructability index than the reference façade.

Keywords

adaptive façade, constructability, redesign, standard product, reverse engineering, DFMA

DOI 10.7480/jfde.2018.3.2530

1 INTRODUCTION

Adaptive façades are considered to be an important step in the development of façade technology. They are receiving increasing attention from researchers and professionals in the building sector, as they provide comfortable interior conditions with low energy consumption. Currently, there are more than five hundred building examples with adaptive shells, according to the climate adaptive building shells database (Loonen, 2013; Attia & Bashandy, 2016). However, these examples are mainly 'experimental, small-scale' or 'high-profile, high-budget' projects (Loonen, Trcka, Cóstola, & Hensen, 2013). Despite their accepted potential for high environmental performance and wide range of technology options from high-tech to low-tech, the practical application of adaptive façades is very limited. A comprehensive literature review is conducted to determine the problems causing this situation, and the findings are listed below:

- Adaptive façades are not clearly defined and resolved in the field of architectural research (Schnädelbach, 2010; Gosztonyi, 2015; Attia, Favoino, Loonen, Petrovski, & Monge-Barrio, 2015). Kolarevic (2015) states that change events are not adequately addressed or explored.
- Designers need to acquire experience and knowledge about designing adaptive façades (Meagher, 2015; Loonen, Favoino, Hensen, & Overend, 2017). However, detailed information about design and construction processes, performance, and post occupancy evaluations of existing cases are lacking in the literature (Attia & Bashandy, 2016; Attia, 2017). Decisions on how adaptive façades are designed, operated, maintained, and assessed remain a challenge (Attia, 2017). Questions such as: what sort of adaptation is needed, what type of behaviour results in the best performance, and what is the maximum acceptable rate of change are still being researched.
- Design and performance evaluation of adaptive façades is a complex task, and existing performance assessment tools are insufficient to evaluate the adaptive façade systems (Loonen et al., 2017; Boer et al., 2011; Struck et al., 2015).
- Standardised procedures, design support tools, and methods are needed for adaptive façade design (Bolbroe, 2014; Loonen et al., 2015)
- Majority of the current examples are project-oriented custom solutions that develop complex one-of-a-kind products and involve innovative technologies, resulting in challenging projects with relatively high risks (Loonen et al., 2013).
- There are social and psychological challenges and barriers related to user interaction (Loonen, 2010; Ogwezi, Bonser, Cook, & Sakula, 2011).

Considering the problems listed above, simple, flexible, and easily accessible solutions are needed with well-described procedures to achieve these solutions to increase the practical application of adaptive façades. Thus, a basis would be provided for adaptive façades to become customised industrial products like the majority of the regular façade systems on the market. In the context of this need, several approaches could be developed to achieve such solutions. One of these solutions is to simplify the design of adaptive façades using products that are based on engineered standard products with the least number of parts and layers. Within the scope of this approach, the term 'product' is used to describe all product levels of façades (Klein, 2013), between different levels of completeness, from material to component, within the building product hierarchy developed by Eekhout (2008). Likewise, the term 'standard product' covers all levels of products with unalterable characteristics and manufacturing processes, ranging from standard material to component (Eekhout, 2008).

In addition to enhancing the feasibility and constructability of adaptive façades, there are several other reasons for proposing the design of adaptive façades using standard products. Anderson (2014) states that standard products are less expensive to design and provide time savings, when design, documentation, prototyping, and testing processes are considered. The overhead cost of purchasing all the constituent parts and the cost of non-core-competency manufacturing can be reduced by using standard products. Suppliers are more efficient within their own specialty, more experienced in using their own products, continuously improve quality, have proven track records on reliability, have dedicated production facilities, produce parts at lower cost, offer standardised parts, and sometimes pick up warranty and service costs (Anderson, 2014). All these features of standard products support the maintenance, repair, and operation processes as well as the manufacturing process.

The aim of this research is to develop a design procedure to support designing adaptive façades with standard products that are available on market, to improve constructability through simplification. At first, a solution is sought for how to design adaptive façades to be manufactured with standard products. Possible solution paths, namely concepts, are identified and one of them is selected for elaboration. Following this, the selected concept is developed with the focus on identification of a design procedure. Various research methods are used within this research. A comprehensive literature review of both façade and product design is performed for concept generation and development. A research through design methodology is adopted, and an iterative loop of development, application test, and review process is carried out for development of process steps, checklists, and templates of the design procedure. Applicability of the design procedure is tested through a case study and evaluated by interviews with experts such as architects and manufacturers. Within this framework, Section 2 presents concept generation, selection, and development processes. Section 3 describes the phases and steps of the redesign procedure, developed for the selected redesign concept. Section 4 presents the application of the redesign procedure through a case study. Section 5 concludes the research with revealing characteristics, benefits, and limitations of the redesign procedure.

2 CONCEPT GENERATION, SELECTION AND DEVELOPMENT

Designing adaptive façades to be manufactured with standard products is an open-ended problem with multiple acceptable solutions. Indeed, a characteristic of architectural design problems is that there are numerous alternatives and many potentially acceptable solutions (Lawson, 1970). The challenge is to find the best solution in relation to the design objectives of the project.

When dealing with an open-ended problem, rather than concentrating initially on a specific solution, it is better to look for as many different solutions as possible (Dandy, Daniell, Foley, & Warner 2018). In this context, some researchers suggest subdividing and structuring the problem-solving process into three different levels: concept level, system level, and material level (Perino & Serra, 2015). From this point of view, this research starts from the concept level and continues down to the system level. The material level is outside the scope of this research, since material development is not intended.

The concept level aims to explore new ideas and visions, and analyses them from a theoretical point of view to obtain information on the working principles (Perino & Serra, 2015). An answer is sought for what would be done to solve the problem, without worrying about how to do it. Concept level studies respectively include collecting ideas and existing concepts, concept generation, and concept selection.

To reveal existing concepts and collect ideas, the mature principles from manufacturing industry are reviewed in the context of the aim of this research. At this stage, the need for customisation of façade design in each project depending on building specifications comes into prominence. In this context, strategies of designing customised products by combining standard products are reviewed from product development literature, to determine possible design approaches.

Ulrich (1992) demonstrated that product variety/customisation can be economically realised with product architecture strategies that provide flexibility in the final assembly process without changing the manufacturing process. In the context of product architecture, customisation by standard products is achieved by modular systems (Ulrich & Eppinger, 2012) and open systems (Koren, Hu, Peihua, & Shpitalni, 2013), and by the production approaches, mass customisation, and mass individualisation, which arise from these product architecture systems. Open systems and modular systems are embraced in architecture in a similar manner (Staib, Dörrhöfer, & Rosenthal, 2008). According to that information, it has been determined that concept studies should focus on the development of the product architecture.

Concept generation study begins after re-stating the research problem in clear, general, and unambiguous terms, and collecting ideas and existing concepts. Within the set of possible solutions, concept alternatives are defined depending on certain variables that are mainly extracted from collected ideas and existing concepts. The number of these variables varies depending on the defined part of the solution set. In this context, nine variables stand out for concept generation to solve this research problem: design types, adaptive façade types, constructability improvement strategies, standard product ratio, functional requirements, performance requirements, demand for customisation, production volume and project budget (Emmitt, Olie, & Schmid, 2004; Charles, Crane, & Furness, 2001; Eekhout, 2008; Dieter & Schmidt, 2012; Jensen, 2014; Firesmith, 2015; Cantamessa & Montagna, 2016; Chen, Peng, & Gu, 2017; Başarır & Altun, 2017). Concepts are generated depending on the value of the choice spectrum for these variables. With respect to this, several concepts are generated, such as open system design, modular system design, and redesign of existing adaptive façades.

After a series of different concept solutions are created for the research problem, the next step is to evaluate, compare, and rank them to define the most reasonable concept for development at system level (Dandy et al., 2018). In evaluation, the 'value', 'benefit', or 'strength' of a concept is measured according to solution objectives of the research problem. In this research, the aim is to select a solution that leads to the fulfilment of following objectives: low development risk, high development capacity, high façade performance, technical availability, and high standardisation. With respect to these objectives, concept selection criteria are determined as development cost, development time, development capacity, performance, technological availability, and complexity level. Generated concepts are evaluated by a weighted decision matrix, and the concept of redesigning dynamic adaptive façades to be manufactured with standard products is chosen for further development.

The advantage of redesign is that the product architecture and a part of the new product is known in advance. There are most likely specific areas or problems to focus on, rather than a completely blank slate. Redesign solutions are generally more feasible and reliable, since they have already been used successfully in existing systems (Han & Lee, 2006). It generally focuses on resolving conflicts between current design objectives and reference design capabilities. Most techniques start by choosing a reference design that reduces conflicts as much as possible. Remaining conflicts, depending upon their degree, are resolved by changing component attributes, replacing components, or changing the structure of the original design (Li, Kou, Cheng, & Wang, 2006).

Concept level of the research is completed by selecting the concept. At the following system level, the selected concept is further investigated and developed with the focus on identification of the redesign procedure. For development of the redesign concept into a redesign procedure, a research-through-design methodology is used. A preliminary case study is conducted to redesign a dynamic adaptive façade to be manufactured with standard products. A systematic design method is not used in this case study. Design diary approach (Pedgley, 2007) is utilised to capture its process steps. Then, these process steps are analysed and grouped, with regard to their intended use and interrelationship. According to this preliminary case study, three fields that need to be improved in the captured redesign process are identified. These are (i) identifying existing parts to be redesigned, (ii) selecting new parts to be used in the redesign, and (iii) solving the contradictions or problems that arise from the reconfiguration process.

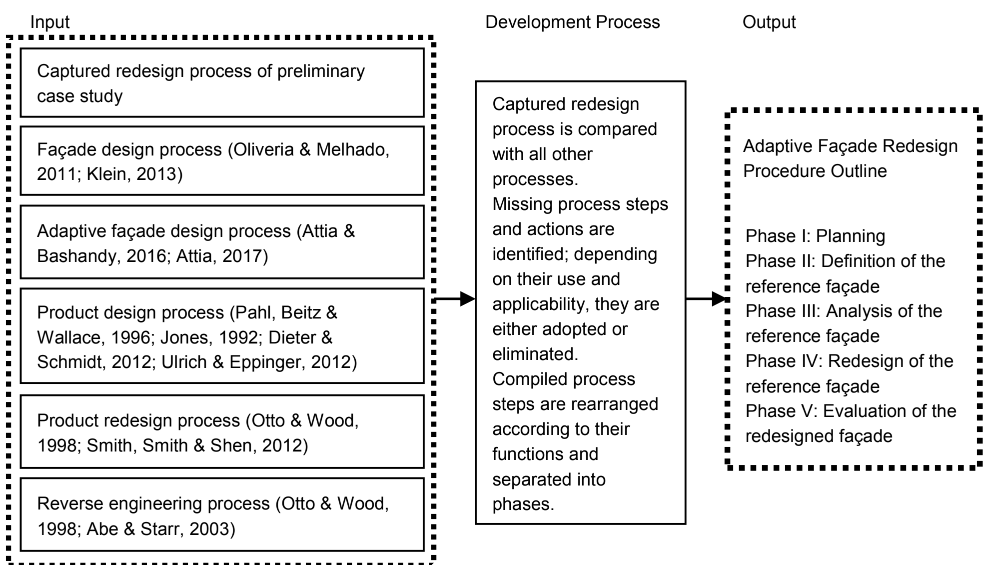


FIG. 1 Adaptive façade redesign procedure outline development

To systematise and improve the captured redesign process of the preliminary case study, façade design, adaptive façade design, and product design methodologies are reviewed first. Captured process steps of the preliminary case study are compared with the reviewed façade design, product design, and redesign process steps, and missing steps and actions are identified. These are subsequently either adopted or eliminated, depending on their use and applicability in the case of adaptive façade design, since not all process steps of product design/redesign are applicable to adaptive façades depending on different characteristics of development processes (Jones, 1992; Ichida & Voigt, 1996; Eekhout, 2008). Reverse engineering processes, which are used in product redesign to reveal the properties and working principles of the existing products, are adopted in the same manner. Compiled process steps are rearranged according to their functions and separated into phases. Thus, a 5-phase adaptive façade redesign procedure is outlined (Fig.1). Then each process phase is developed separately, according to the projected outputs of the phases.

After the redesign procedure has been outlined, studies are initiated on fields that need improvement according to the preliminary case study. Approximately sixty design methodologies have been reviewed in the context of this research problem (Tomiyama et al., 2009; Dieter & Schmidt, 2012; Tooley & Knovel, 2010; Eekhout, 2008; Ong, Nee, & Xu, 2008; Natee, Low, & Teo, 2016). Since the first field to be improved is the identification of the existing parts to be redesigned through elimination or replacement, research is initially focused on product simplification methods. Systematic problem-solving and design improvement methods related to manufacture and assembly are analysed to determine which of them could be utilised to improve constructability through simplification. Based on this, the design for manufacture and assembly (DFMA) method, which focuses on the same goals as the constructability concept, developed by O'Connor, Rusch, and Schulz (1987), and intended to adapt into architectural design in various researches to increase the constructability (Fox, Marsh, & Cockerham, 2001; Gerth, Boqvist, Bjelkemyr, & Lindberg, 2013), is selected to be adapted into the redesign process.

DFMA is a design-review method with two components: design for manufacture (DFM) and design for assembly (DFA). DFMA has three beneficial impacts on design: (i) reducing the number of parts, (ii) reducing the costs, and (iii) increasing reliability and quality of design through the simplified production process. In order to simplify a product's structure, the DFA method recommends a functional analysis of each part in the assembly to identify and eliminate parts that do not exist for fundamental reasons. Furthermore, DFMA manuals comprise comparison metrics for generic material, process, and component types and design evaluation metrics. (Otto & Wood, 1998)

Elimination or replacement of parts and reconfiguration of the system during the redesign process can lead to contradictions/problems which require design revisions. To support that process, systematic problem-solving methods are analysed. Theory of Inventive Problem Solving (TRIZ), which is claimed as a powerful support in tackling technical problems and increasing creativity (Chechurin & Borgianni, 2016), is selected for adaptation to the redesign process. The method works by restating the specific design task in a more general way and then selecting generic solutions from identified principles, previously-identified evolutionary patterns, and databases of designs and patents collected and abstracted from a wide range of technologies. TRlZ provides several problem-solving tools, such as Inventive Principles for overcoming technical contradictions, Separation Principles for overcoming physical contradictions, Inventive Standards or Scientific Effects for coping with a missing function, and Trends of Technological Evolution for solving technical and physical contradictions (Lucchetta Bariani, & Knight, 2005).

To develop the fields that were determined through the preliminary case study, the above-mentioned modules and tools of the DFMA and TRIZ methods, which are expedient for research purposes, are integrated into the redesign procedure outline. Furthermore, to support the selection of parts for replacement in redesign, part selection factors are compiled from literature. By adding checklists and templates to the design steps, improvements are made to facilitate the implementation of the redesign procedure. For a detailed examination, each phase of the procedure is subjected to application testing. An iterative loop of development, application test, and review process is carried out for development of the process steps. The steps that are taken in the development of the redesign procedure, depending on the phase development are shown in detail in the following figures (Fig. 2, Fig. 3, Fig. 4, Fig. 5, and Fig. 6).

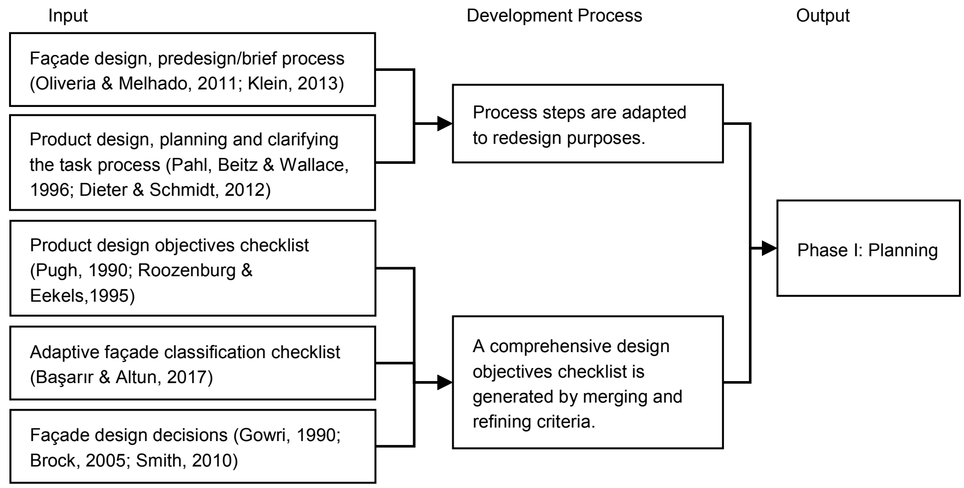


FIG. 2 Phase I: Planning, development of process steps

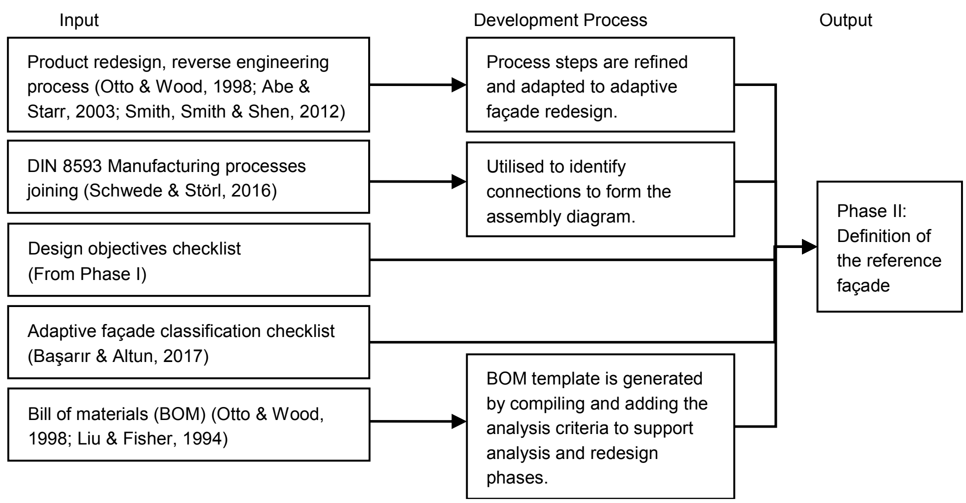


FIG. 3 Phase II: Definition of the reference façade, development of process steps

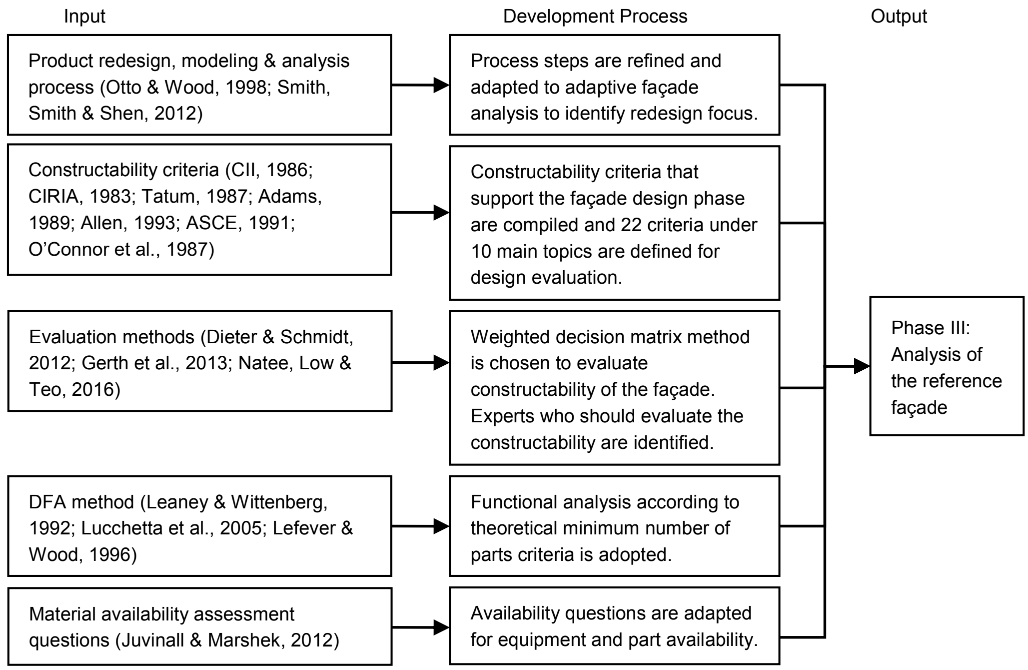


FIG. 4 Phase III: Analysis of the reference façade, development of process steps

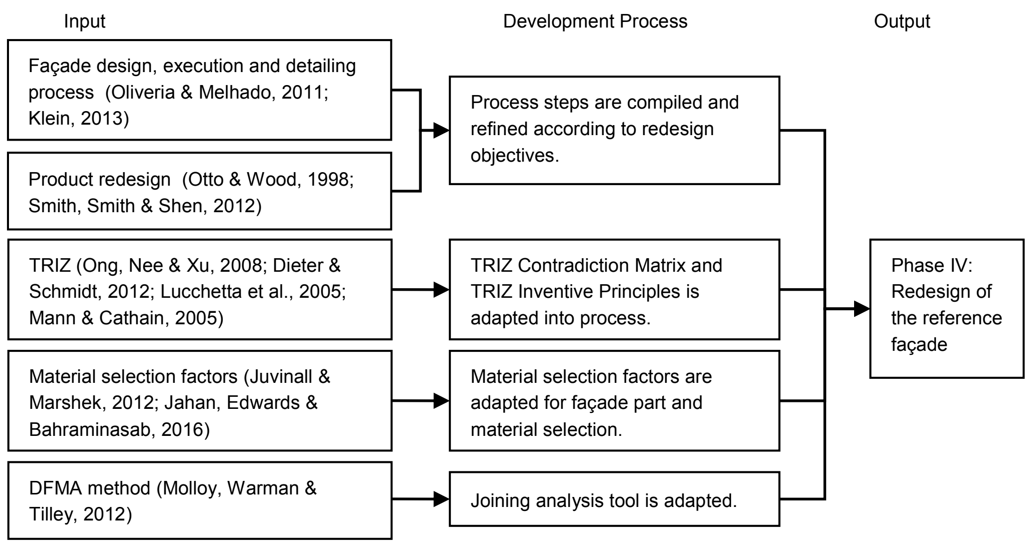


FIG. 5 Phase IV: Redesign of the reference façade, development of process steps

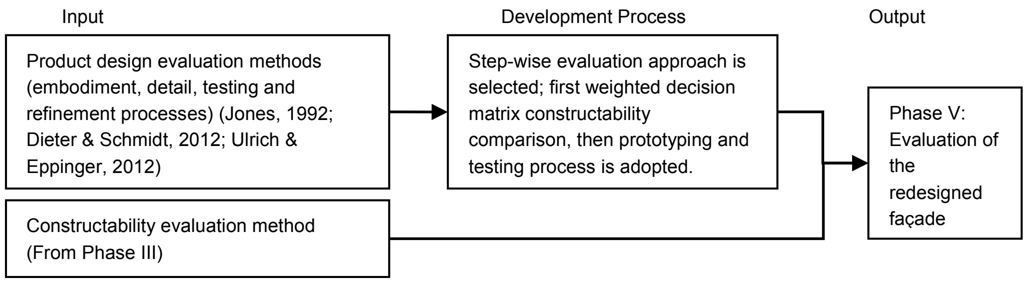


FIG. 6 Phase V: Evaluation of the redesigned façade, development of process steps

3 A REDESIGN PROCEDURE TO MANUFACTURE ADAPTIVE FAÇADES WITH STANDARD PRODUCTS

A redesign procedure with a structured approach towards manufacturing adaptive façades with standard products is developed as presented in Section 2. It is based on the organisation of form, elimination, replacement or addition of parts, and reconfiguration, depending on the design objectives. It consists of five phases and their application steps. Even though the process is linear theoretically, there is a back coupling between and within the phases in practice. Application steps and outputs of each phase are explained in the following sections.

3.1 PHASE I: PLANNING

The aim of this phase is to determine the design objectives and constraints of the façade required for the developing architectural project, and in this context selecting the most proper existing adaptive façade for redesign. First, factors, namely the design objectives, affecting the decisions of façade design and defining the characteristics of the façade, are revealed. A checklist approach is adopted for that purpose. The checklist consists of a comprehensive list of design objectives with 22 factors, such as built environment conditions, performance requirements, material properties, regulations, standards, building and façade characteristics, aesthetics, and cost per unit. Based on the data obtained from the checklist, an existing adaptive façade that most closely meets the design objectives is selected as the reference façade for redesign.

3.2 PHASE II: DEFINITION OF THE REFERENCE FAÇADE

An extensive understanding of the reference façade is needed to lead the redesign process. This phase intends to provide an understanding of the design rationale that motivated the existing design and physical system of the reference façade. It leads to a comprehension of the "whys" that motivated the "hows" of the reference façade. Definition of the reference façade is achieved through the concept of reverse engineering. Reverse engineering, wherein a product is observed, disassembled, analysed, and documented in terms of its form, components, physical principles, functionality, manufacturability, and assemblability, initiates the redesign process. Definition studies are based on the design, production, and installation details obtained from the designers, contractors, and manufacturers.

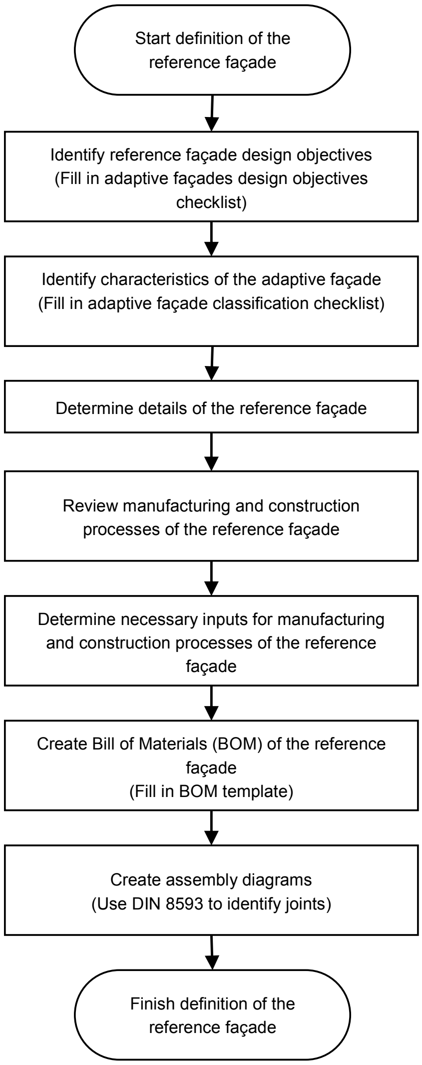


FIG. 7 Phase II: Definition of reference façade, process flowchart

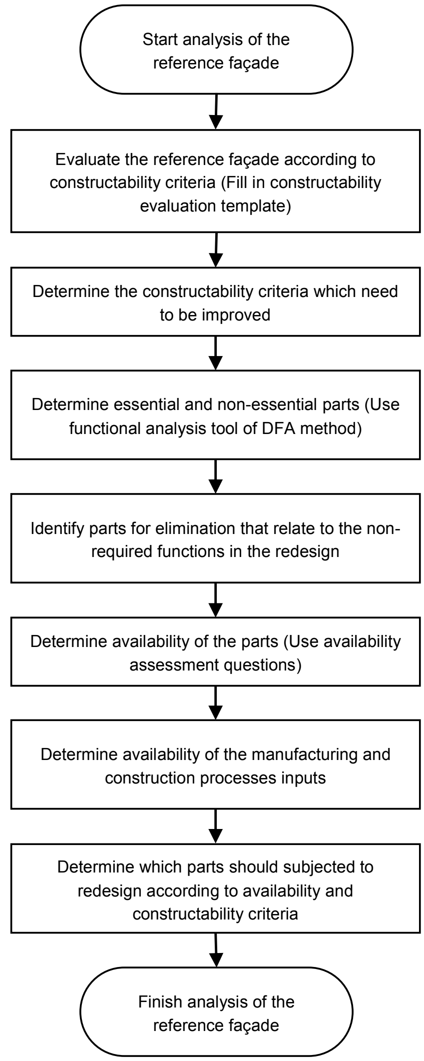


FIG. 8 Phase III: Analysis of reference façade, process flowchart

A comprehensive collection of information on the reference façade is undertaken at this phase. The adaptive façade design objectives checklist structured in the planning phase is utilised to establish the factors that motivated the reference façade design. The adaptive façade classification checklist is used to identify adaptive façade characteristics. Details of the façade system are identified and examined. Manufacturing and construction processes of the façade system are reviewed and the necessary inputs, such as equipment, labour, and funds for these processes are determined.

One of the most important steps in this phase is generating a bill of materials (BOM) for the reference façade. BOM is used for displaying data inputs and outputs, defining key characteristics of parts and structuring part relationships in the manufacturing industry. The BOM of the reference façade is generated according to BOM template to support redesign decisions. The BOM template contains information about sub-assemblies, parts, part numbers, functions, quantity, unit of measure, materials, manufacturing process, production, and procurement type, which describes if a particular part has been purchased or manufactured.

As well as identifying the parts that form the façade system, connections of the parts with each other and with other building components should be identified. Type of joints between façade parts are identified by assigning manufacturing processes according to DIN 8593, and assembly diagrams are created.

The flowchart showing all process steps of the phase is given in Fig. 7. Upon completion of this phase, all the information necessary for the analysis of the reference façade is defined.

3.3 PHASE III: ANALYSIS OF THE REFERENCE FAÇADE

As a characteristic of redesign, the product architecture and a fraction of the redesigned façade system is known in advance, and conversely, the parts that need to be eliminated or replaced by standard products must be determined. Identifying which parts are the focus of the redesign is important, as well as recognising the redesign objectives.

Analysis of the reference façade starts with the constructability evaluation, which is made according to 22 constructability criteria used in the detailing process in architectural design, such as the use of minimum number of parts and the use of readily available products in common sizes and configurations. A constructability evaluation template is generated according to a weighted decision matrix method to support this step. A constructability index is calculated by the constructability evaluation; as the index value converges from zero to one, the level of constructability increases.

An important issue to be considered is that the nature of the constructability evaluation mostly depends on the level of expertise of the evaluator (cf. Dorst, 2004), therefore choice of the evaluator should be done very carefully. At this point, level of expertise of the designer who is responsible for the redesign should be identified according to the knowledge required about the design, manufacturing and construction processes of the reference façade. If necessary, experts should be identified on subjects that require deeper knowledge. Consequently, the evaluation should be carried out by the designer together with an expert team.

The purpose of the evaluation is to clarify to what extent the reference design can achieve the constructability criteria and set a course of redesign. Based on this evaluation, the constructability criteria, to which the reference façade design should be improved, are determined. Generally, simplification, standardisation, use of easy-to-find products, and use of enhanced details are the most prominent constructability criteria for reducing the complexity of the reference façade and supporting production with standard products.

The following step of this phase is to determine which parts of the façade will be subject to redesign. DFA function analysis is performed to determine essential and non-essential parts. In this phase of the analysis, technical or economic limitations are largely ignored to encourage breakthrough thinking by removing the mental constraints of existing solutions. Then, the parts that provide the functions that are not required in the redesign are defined by comparing the design objectives of redesign and reference design. With the data obtained from the BOM, availability of the parts that form the façade is assessed according to the availability questions. Availability of manufacturing and construction process inputs is evaluated to determine redesign constraints.

The steps of this phase, which analyse the reference façade according to the constructability, functionality, and availability criteria, are shown in Fig. 8.

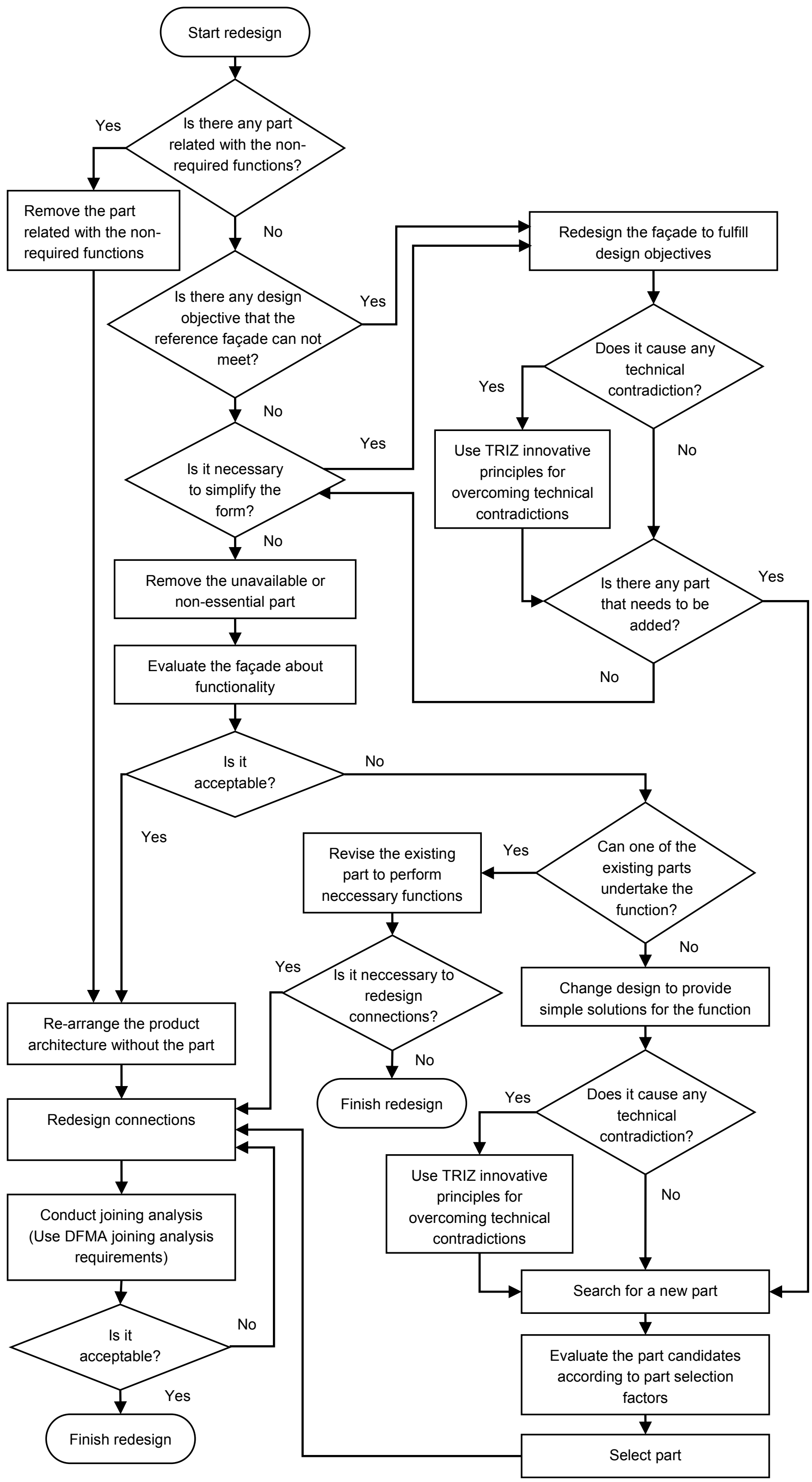


FIG. 9 Phase IV: Redesign of the reference façade, process flowchart

3.4 PHASE IV: REDESIGN OF THE REFERENCE FAÇADE

Redesign of a system is a special case of design activity, which includes not only choosing the parts, but also managing their connections, assigning functions, and reconfiguring the system. Parametric, adaptive, or original redesign solutions can be achieved according to the changes made in the reference façade. The redesign approach adopted in this research is based on the organisation of form, elimination, replacement or addition of parts, and reconfiguration, depending on the design objectives.

First, the parts that provide the functions that are not required depending on the function analysis are removed from the system. If there are functions that the reference façade does not provide, means of meeting these through use of existing parts are sought. The form is arranged to simplify the design. Contradictions encountered in the redesign are eliminated with TRIZ tools. New parts are identified as substitutes for those that cannot be supplied feasibly by current sources. Part selection factors, such as material properties, cost, and joinability, are used to evaluate candidates. Parts are checked for compatibility; their connections are designed and subjected to joining analysis according to DFMA joining analysis requirements, such as load bearing capacity, corrosion resistance, and maintainability. The flowchart showing the process steps is given in Fig. 9.

3.5 PHASE V: EVALUATION OF THE REDESIGNED FAÇADE

In this phase, the façade system obtained as a result of the redesign activities is evaluated in relation to the design objectives. A stepwise evaluation approach is performed. First, constructability evaluation and constructability index comparison are conducted. The constructability evaluation of the redesigned system is repeated with the same method used in Phase 3. The purpose is to clarify to what extent the constructability of the redesigned façade has changed in relation to specific constructability criteria. If the evaluation results do not meet the design objectives and a significant constructability improvement has not been achieved, redesign iterations are needed. If the constructability improvement is in the acceptable range and the scope of the changes requires the performance of the façade to be tested, then prototyping and performance testing processes are performed according to the test plan. The test plan gives a description of the test types to be performed and outlines when the test will be done. If the performance test results are acceptable, the detailed design is finalised, and documents related to production, assembly, transportation, and operation are fully prepared.

4 A CASE STUDY

Application of the redesign procedure is demonstrated through a case study. The actions performed in the process steps depending on the phases of the procedure are described in the following sections.

4.1 APPLICATION OF PHASE I: PLANNING

The aim of this phase is to determine the design objectives of the required façade system and, in this context, to select the most proper existing adaptive façade for redesign. For this purpose, it is recommended that the design objectives checklist be used for a comprehensive identification of the required façade. Since, in this case, the selection of the existing adaptive façade to be redesigned is not dependent on any particular project, the design objectives checklist is not needed in this phase. Instead, the existing adaptive façade selection is made on the basis of having access to design and production details of the façade that enables the redesign. In this context, the adaptive façade of the Training Academy, designed by Ackermann und Partner and located in Unterschleißheim, Germany, is selected as the reference façade for the case study (Fig. 10). It is assumed that the reference façade is to be redesigned for a project in Turkey, with consideration given to intellectual property rights. It is known that not all the design parameters of the reference façade are compatible with a project in Turkey. Even so, to simplify the redesign process, it is assumed that the environmental parameters and the design objectives remain the same for this case study. The focus of the redesign is using standard products and simplifying the system to improve the constructability of the reference façade in market conditions of Turkey.

a *b*

FIG. 10 a) Front view and b) corridor view of the adaptive façade of the Training Academy in Unterschleißheim *(Schulungsgebäude in Unterschleißheim, 2018)*

4.2 APPLICATION OF PHASE II: DEFINITION OF THE REFERENCE FAÇADE

In this phase, the reference façade is defined by application of the process steps shown in Fig. 7, in terms of the data and details obtained from the literature (Schumacher, Schaeffer, & Vogt, 2010; Schittich, 2005) and the assumptions made based on them. As a first step, design objectives and constraints that are effective in the design of the reference façade are described. Here, the design objectives checklist is used to systematically present the data obtained from the literature and to provide a comprehensive description. In the checklist of 22 criteria, the reference façade is defined in the context of 9 criteria; those most relevant for redesign purposes are shown in Table 1. Following this, the characteristic features that define the change event performed by the adaptive façade are revealed based on the classification checklist. The simplified adaptive façade classification checklist, based on the characteristics of the reference façade, is given in Table 2. The details of the adaptive façade are compiled from the literature (Fig. 11 and 12).

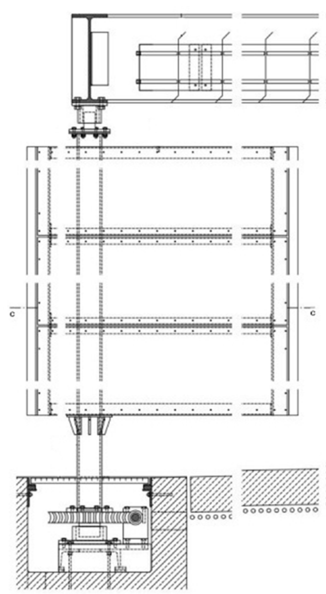
CRITERIA	EXPLANATORY QUESTIONS	TRAINING ACADEMY
Environment	To which environmental influences is the façade subjected during the operation, manufacturing, storage, and transportation?	Wind, temperature, vehicle vibration
Performance/ Functions	Which function(s) does the façade have to fulfil?	Be wide enough to allow the passage of vehicles, prevent solar gains, provide panel load support, and automatic movement according to position of sun
	By what parameters will the functional characteristics be assessed?	Dimensions, load capacity, movement capacity, solar shading
Size and Weight	What are the dimensions of the proposed façade panel?	h: 6.67m; w: 2.50m; d: 0.25m
	What is the weight of the proposed façade panel?	1000kg
	Does production, transport, or use process define limits in relation to the maximum dimensions or weight? Explain the potential constraints.	Be wide enough to allow the passage of vehicles, be within the dimensions of road transfer, and must be lightweight.
Aesthetics, Appearance, and Finish	What are the aesthetic preferences? Should the façade fit in with an architectural style or concept?	Sail-like sunscreen panels
Social and Political Implications	Is there a social idea that the design should reflect?	Symbolic value: Sail-like sunscreens symbolize the technical mobility of the training academy and symbolize the dynamic mobility of the BMW Group.
Quantity	What is the size of the production?	43 units of sunscreen panel

TABLE 1 Design objectives related with the redesign of the reference façade

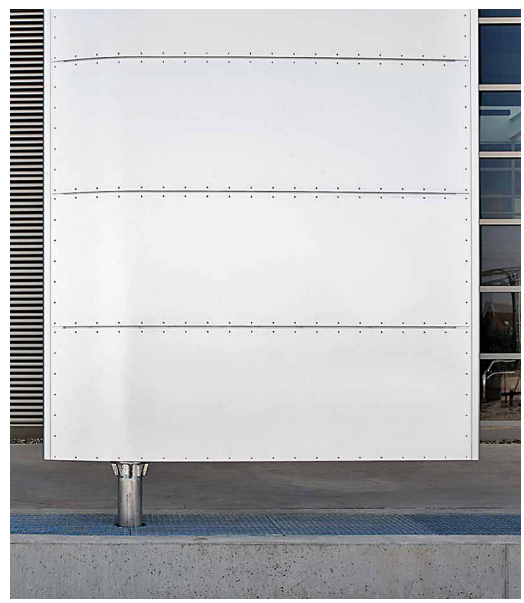
CLASSIFICATION CRITERIA	TRAINING ACADEMY ADAPTIVE FACADE CHARACTERISTICS
Elements of Adaptation	Sunscreen (Building component)
Spatial Morphology	Not integrated to the façade; outside of the façade plane
Agent of Adaptation	Individual inhabitants, exterior environment, solar radiation
Response to Adaptation Agent	Dynamic
Type of Movement	Rotation
Size of Spatial Adaptation	Metres
Limit of Motion	Inclusive (180 degrees on the vertical shaft)
Structural System for Dynamic Adaptation	Plate structure swivel around a vertical shaft
Type of Actuator	Motor-Based
Type of Control/Operation	Direct and indirect control
System Response Time	Seconds to minutes
System Degree of Adaptability	Hybrid
Level of Architectural Visibility (Rush Classification)	Visible, with location or orientation change
Effect of Adaptation	Prevent solar gains
Degree of Performance Alteration	Medium*
System Complexity	Level 2*

* These assessments are hypothetical; Level 2 describes relatively simple systems in the ordinal scale of 1-4

TABLE 2 Presentation of the reference façade characteristics, which define the change event according to adaptive façade classification criteria.

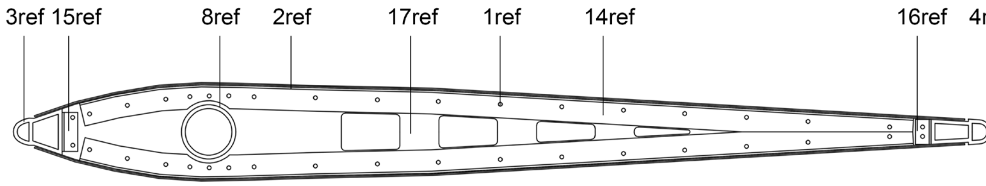


a



b

FIG. 11 a) Section drawing *(Schittich, 2005)* and b) partial view from the bottom of the reference façade sunscreen panel (*Schittich,2005; Schulungsgebäude in Unterschleißheim, 2018)*



1ref) Rivet	4ref) Edge profile (B)	15ref) T profile (B)
2ref) Aluminium sheet cladding	8ref) Tube profile	16ref) T profile (C)
3ref) Edge profile (A)	14ref) T profile (A)	17ref) Hollow rib

FIG. 12 Reference façade sunscreen panel cross section detail *(Adapted from Schittich, 2005)*
*Part numbers are linked with the BOM and 'ref' indicates the parts of the reference design.

Project Name:	Training Academy in Unterschleißheim										
Total Part Count:	1264										
				Dimensions (mm)							
Part No	Part Name	Quantity	Function	Width	Length	Height	Weight	Material	Manufacturing Process	Supplier	Unit Cost
A	Cladding Assembly										
1	Rivet	50x16	Join parts Allow damage free movement					Aluminium	Standard		
2	Aluminium sheet cladding	16	Provide sun shading	t:3	2400	83		Anodized Aluminium	Standard		
B	Edge Profile Assembly										
1	Rivet	32x2	Join parts Allow damage free movement					Aluminium	Standard		
3	Edge profile A	1	Create stiffness perpendicular to surface Prevent material deterioration	120	125	6670		Aluminium	Custom		
4	Edge profile B	1	Create stiffness perpendicular to surface Prevent material deterioration	65	155	6670		Aluminium	Custom		
C	Vertical Shaft Assembly										
5	Circular plate A	1	Allow joining of parts	Ø240 outer; Ø140 inner		10		Aluminium	Custom		
6	Circular plate B	1	Bear structural loads	Ø250 outer; Ø140 inner		10		Aluminium	Custom		
7	Triangular plate	8	Transfer load	t:9	45	100		Aluminium	Custom		
8	Tube profile	1	Bear structural loads Allow movement	Ø140 outer; Ø120 inner		7320		Aluminium	Standard		
D	Top And Bottom Rib Assembly										
1	Rivet	38x2	Join parts Allow damage free movement					Aluminium	Standard		
9	L profile A	2	Allow joining of parts Transfer load	60 (t:5)	2130	100		Aluminium	Custom		
10	L profile B	2	Allow joining of parts Transfer load	60 (t:5)	2130	100		Aluminium	Custom		
11	L profile C	2	Allow joining of parts Transfer load	40 (t:5)	100	100		Aluminium	Standard		
12	L profile D	2	Allow joining of parts Transfer load	40 (t:5)	50	100		Aluminium	Standard		
13	Solid rib	2	Bear structural loads Create stiffness perpendicular to surface	235	2215	t:5		Aluminium	Custom		
E	Mid Ribs Assembly										
1	Rivet	38x7	Join parts Allow damage free movement					Aluminium	Standard		
14	T profile A	2x7	Allow joining of parts Transfer load	60 (t:5)	2130	100		Aluminium	Custom		
15	T profile B	1x7	Allow joining of parts Transfer load	40 (t:5)	100	100		Aluminium	Standard		
16	T profile C	1x7	Allow joining of parts Transfer load	40 (t:5)	50	100		Aluminium	Standard		
17	Hollow rib	1x7	Bear structural loads Create stiffness perpendicular to surface	235	2215	t:5		Aluminium	Custom		

FIG. 13 The BOM of one sunscreen panel of the reference façade

After this point, the processes that the reference façade has passed, in reverse order from the installation at the construction site, are examined and the system is theoretically taken apart. Manufacturing and construction processes of the sunscreen panels are investigated with the experts and the necessary inputs, such as equipment and skilled labour, are determined. Accordingly, relatively simple equipment is needed in these processes, such as an aluminium welding machine, a rivet machine, and a low-capacity crane. The BOM of one sunscreen panel is created according to the BOM template and in the order of theoretical take-apart process (Fig. 13). With the information obtained from the previous process, the assembly diagram is created by defining the joints of the parts according to DIN 8593.

4.3 APPLICATION OF PHASE III: ANALYSIS OF THE REFERENCE FAÇADE

Based on the data compiled at the previous phase, constructability, availability, and function analysis of the reference façade is performed during this phase, to determine the redesign strategy and the parts to be focused on during redesign. The process flow is carried out according to the steps shown in Fig. 8.

First, the experts to evaluate the constructability of the reference façade, using the approach explained in Section 3.3, are chosen. Since the sunscreen panels are completely made from aluminium material, constructability evaluation is carried out by aluminium profile and façade manufacturers operating in Turkey who are engaged with aluminium processing and have sufficient knowledge about manufacturing and construction processes. As a result of the evaluation, it is stated that due to the sail-like form of sunscreen panels, materials need custom shaping, which complicates the production process. Furthermore, the assembly process gets complicated due to the excessive number of assembly parts. In this context, the constructability criteria on which to focus the redesign are chosen to be simplification and standardisation, in order to manufacture the system with readily available products in common sizes and configurations, and with the minimum number of parts for assembly. Thereafter, essential and non-essential parts are identified using the DFA functional analysis tool (Table 3).

ESSENTIAL PARTS	BOM Part Number	NON-ESSENTIAL PARTS	BOM Part Number
Aluminium sheet cladding	2	Rivets	1
Tube profile (base part)	8	Edge profiles (A, B)	3, 4
Solid ribs	13	Circular plates (A, B)	5, 6
Hollow ribs	17	Triangular plates	7
		L profiles (A, B, C, D)	9, 10, 11, 12
		T profiles (A, B, C)	14,15,16

TABLE 3 Essential and non-essential parts of the reference façade according to DFA functional analysis

Since the redesign aims to have the same functional characteristics as the reference façade, there are no unrequired functions, nor parts related to them. The availability assessment of the parts is done on an ordinal scale of 1-5, in the context of the answers given to the seven availability questions. The scale defines the cases in which 5 represents the highest, and 1 represents the lowest availability. According to the assessment made with the experts, this value is set at 3 (medium availability), since each part except the aluminium tube requires geometric configuration and custom shaping, and the complexity level of these processes are considered. Required equipment in the production, assembly, and installation processes are also available in Turkey's market conditions, but their cost should be considered.

As a result of the analysis carried out in this phase, the following redesign strategies are identified: (i) removal of non-essential parts from the system, (ii) replacement of parts, which cannot be removed from the system and require special shaping, with standard products, and (iii) simplification of the panel form.

4.4 APPLICATION OF PHASE IV: REDESIGN OF THE REFERENCE FAÇADE

In the redesign phase, the process given in Fig. 9 is repeatedly used and various alternatives are developed within the strategies determined during the analysis phase. The form of the sunscreen is rationalised in such a way that it would not cause a fundamental change at its functions. The form change also removes the necessity of custom shaping of the adjoining parts: T profile A, L profile A and B, which are identified in Fig. 13.

The next step after the form change is to remove unavailable or non-essential parts from the system. In this context, custom edge profiles are evaluated first. Without their functions, the system is not considered acceptable, and the functions could not be transferred to any of the existing parts. Therefore, standard products are sought to undertake the functions of these parts. Since they provide integrity of the frame and increase its strength by creating stiffness perpendicular to the surface, as well as protecting the edges of the aluminium sheet cladding from deterioration, proper products that could undertake both functions could not be found in the product catalogue survey. So, it is decided that the functions should be met by separate products. With this new point of view, another product catalogue survey is conducted, and this time suitable products are found. Since only one profile pair is considered feasible for replacement, product selection assessment is not needed. The function of preventing material deterioration is provided by a standard profile produced for use in another industry, and the function of creating stiffness perpendicular to the surface is provided by a standard U profile. Joining of these two profiles is provided by riveting. A joining analysis is performed according to the DFMA joining analysis criteria that are highlighted in the context of this detail, such as load bearing capacity, and the joining is found feasible. This constitutes the first redesign alternative and is detailed as shown in Fig. 14.

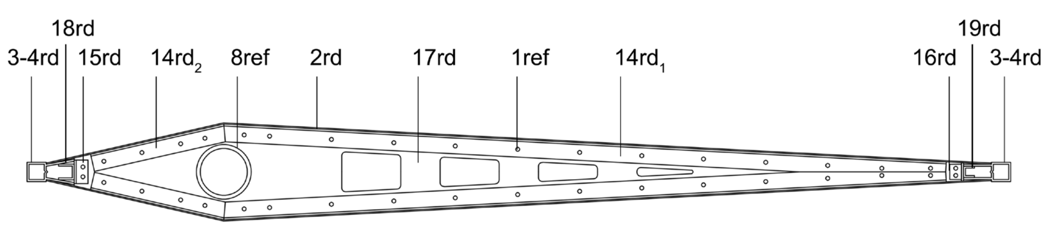


FIG. 14 Redesigned sunscreen panel cross section detail, alternative 1
*Part numbers are linked with the reference BOM, and "ref" indicates the unmodified parts of the reference façade and 'rd' indicates the replaced or modified parts of the redesign.

Furthermore, solutions are investigated to reduce the number of parts by transferring the assembly function of the T and L profiles to the ribs. Thus, all T and L-section aluminium profiles and the rivets which join them to the ribs could be eliminated from the system. In this context, three solution alternatives are developed: (i) welding aluminium plates to the rib, (ii) bending the edges of the rib to give a shape of L, and (iii) to obtain the T shape at the edges, replacing the original 5mm rib with two 2.5mm ribs which are bent in L form from their edges and riveted to each other. Consequently, the whole redesign process resulted in four redesign alternatives.

4.5 APPLICATION OF PHASE V: EVALUATION OF THE REDESIGNED FAÇADE

The four redesign alternatives that resulted from the redesign process are introduced into the evaluation process during this phase. It is assumed that there is no significant change in the adaptive performance of each alternative, since the movement mechanism, type of movement control, overall dimensions, and the aluminium sheet surface cladding of the sunscreen panels remain unchanged. With regard to the evaluations of the experts, it is revealed that modifying the ribs to undertake the assembly function is a promising idea in terms of reducing the number of parts and assembly steps; however, aluminium welding is not preferred over riveting in terms of application difficulty and cost. Furthermore, it is stated that the bending alternatives should be subject to some evaluations to determine their applicability, such as the complexity that the bending process will bring on the rib shaping and calculation of the changing load bearing capacities. As a result of these evaluations, only the first alternative, with form change and part replacement, is subjected to constructability evaluation. The capability of using products in common sizes and configurations, brought by the form change, and replacement of custom profiles with standard profiles, improved the simplification and standardisation scores of the system. On the other hand, number of parts and assembly steps of the system have increased, since the function of the custom profile is fulfilled by two standard profiles and they are joined by riveting. In this respect, the points taken from the use of a minimum number of parts criterion have been reduced. Nevertheless, the redesigned sunscreen panel has a higher constructability index than the reference design. It is also expected that the manufacturing costs are reduced by the redesign. Consequently, this redesign alternative does not require further evaluation such as performance testing. However, it is considered useful to develop alternatives to reduce the number of the parts.

5 CONCLUSION

Despite their high environmental performance, practical application of adaptive façades is very limited. The majority of the current examples are developed by engineer-to-order design processes, as project-oriented, custom, and complex solutions. Even though its translation into a ready-for-market product is very challenging, this is still considered to be a very promising idea. As a starting point, simple, flexible, and easily accessible solutions are needed to increase the feasibility of adaptive façades. One of these solutions is to simplify the design of adaptive façades using engineered standard products with the least number of parts and layers. In this context, this paper aimed to develop a design procedure to support designing adaptive façades with standard products to improve constructability through simplification.

The research starts by generating concepts for designing adaptive façades to be manufactured using standard products. Among several concepts, 'redesigning dynamic adaptive façades' is selected for further investigation, in terms of solution goals determined for this research. A preliminary case study is conducted without a systematic method to redesign an adaptive façade to be manufactured with standard products. The steps of the redesign process are captured and analysed, and the aspects that need improvement are revealed. To systematise and improve the captured design process, façade design, product design, product redesign, systematic problem-solving, and design improvement methods are analysed and adapted to the adaptive façade redesign process. Thus, a redesign procedure is generated by the combined application of DFMA and TRIZ in the synthesis of reverse engineering and redesign processes.

Subsequent to the procedure development, its application is tested through a case study. Each phase is evaluated separately in terms of functionality and ease of application. Determining the factors, namely the design objectives, affecting the decisions of façade design of the developing architectural project in Phase I, enables a comparison with the design objectives of the existing façades. This makes it possible to recognise the possible contradictions in the first stage of redesign and to take precautions against them. It is also useful for selecting the most proper existing adaptive façade as a reference façade for redesign. Furthermore, redesign can be misleading without an extensive understanding of the reference façade. Phase II and III provide an extensive analysis of the reference façade and become vital in making the right redesign decisions. The checklists, templates, and evaluation criteria given in the procedure ease its application. In general, the process steps are well described and can be easily followed except for some cases described below. Among them, the application of Phase IV, the redesign, is relatively complicated as it requires multiple iterations to achieve a reasonable solution. Nevertheless, the several redesign alternatives that followed as an outcome of the case study have demonstrated that it is applicable and useful from this point of view. Phase V provides a framework for evaluation of the redesign. Its stepwise evaluation approach avoids unnecessary workload. The case study has resulted in a redesign which has a higher constructability index and a higher potential for feasible manufacturing in Turkey's construction market compared to the reference façade. In this context, the use of the procedure has yielded positive results.

The redesign procedure is both product and process focused, representing a structured approach to manufacturing adaptive façades with standard products. It supports the improvement of constructability through system simplification. It is proposed that it be used by the designer responsible for the adaptive façade design, with experts who have a comprehensive knowledge on required subjects, such as materials, production techniques, and local market conditions. It is sequential in theory; each phase produces input for the next. However, multiple iterations within and between the phases may be needed to achieve the best solution. Although it is assumed that such systematic methods could restrict creativity and innovation, it is a case-based approach, and use of the procedure may also provoke thought by imposing actions that the designers had not previously conceived. Furthermore, the procedure is suitable for expansion. It can accommodate additional tools for design analysis to support unforeseen design objectives. It can also be utilised for original adaptive façade design after determining the product architecture, to analyse and improve the design for manufacturing.

Besides all the promising features, the procedure has some limitations. The quality of the redesigned adaptive façade cannot be isolated from the reference façade, nor from the level of expertise of the designers using the procedure. Therefore, the right choice of experts and reference façade has a great impact on the quality of the redesign. Although redesign is a widely used method in product design, its practical application in adaptive façade design is currently limited due to the lack of detailed information about existing adaptive façades. In addition, the intellectual property rights of the reference façade must be considered in the redesign. Moreover, the absence of product databases makes it difficult to select products in a controlled way, which in turn affects the connection design and can give rise to extra design iterations.

References

Abe, T., & Starr, P. (2003). Teaching the writing and role of specifications via a structured teardown process. *Design Studies,* 24(Common Ground), 475-489. doi:10.1016/S0142-694X(03)00037-1

Adams, S. (1989). *Practical Buildability (CIRIA Building Design Report).* London, UK: Butterworths -Heinemann Ltd

Allen, E. (1993). *Architectural Detailing: Function, Constructability, Aesthetics*. Hoboken, New Jersey: Wiley.

Anderson, D. M. (2014*). Design for Manufacturability: How to Use Concurrent Engineering to Rapidly Develop Low-Cost, High-Quality Products for Lean Production*. [N.p.]: Productivity Press.

ASCE. The Construction Management Committee, Construction Division (1991). Constructability and constructability programs: White paper. *Journal of Construction Engineering and Management*, 117(1), 67-89.

Attia S. (2017). Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. *QScience Connect, Shaping Qatar's Sustainable Built Environment*, 2 (6), 1-13 Retrieved from http://dx.doi.org/10.5339/connect.2017.qgbc.6

Attia, S., & Bashandy, H. (2016). Evaluation of adaptive facades: The case study of AGC Headquarter in Belgium. In eds. Belis, J. & Louter, C., *Challenging Glass 5 -– Conference on Architectural and Structural Applications of Glass*. Ghent, Belgium: Ghent University.

Attia, S., Favoino, F., Loonen, R.C.G.M., Petrovski, A., & Monge-Barrio, A. (2015). Adaptive facades system assessment: An initial review. 10th Conference on Advanced Building Skins, 3-4 November, 1265-1273, Bern, Switzerland.

Başarır, B., & Altun, M.C. (2017). A classification approach for adaptive façades. In Tavil, A., & Celik, O.C. (Eds.), *ICBEST Istanbul: Interdisciplinary Perspectives for Future Building Envelopes*, Istanbul, Turkey: Istanbul Technical University.

Boer, B. D., Ruijg, G., Loonen, R. R., Trcka, M. M., Hensen, J. J., & Kornaat, W. (2011). Climate adaptive building shells for the future – optimization with an inverse modelling approach. In *Proceedings ECEEE Summer Study 2011*, Belambra Presqu'île de Giens, France, June 2011, 1413-1422

Bolbroe, C. (2014). Adaptive Architecture. *Non-Refereed Proceedings of the 2nd Media Architecture Biennale Conference: World Cities.* pp:13-16. Aarhus, Denmark

Brock, L. (2005). *Designing the Exterior Wall: An Architectural Guide To The Vertical Envelope*. Hoboken, N.J: John Wiley.

Cantamessa M., & Montagna F. (2016). Design and redesign of product architecture. In: *Management of Innovation and Product Development.* London: Springer. doi:10.1007/978-1-4471-6723-5_16

Charles, J. A., Crane, F. A. A., & Furness J. A. G. (2001). *Selection and Use Of Engineering Materials*. Oxford: Butterworth-Heinemann

Chechurin, L., & Borgianni, Y. (2016). Understanding TRIZ through the review of top cited publications. *Computers in Industry,* 82119-134. doi:10.1016/j.compind.2016.06.002

Chen, Y., Peng, Q., & Gu, P. (2017). Methods and tools for the optimal adaptable design of open-architecture products. *The International Journal Advanced Manufacturing Technology*, (1-4), 991. doi:10.1007/s00170-017-0925-6

CII (1986). *Constructability: A Primer*. Austin, TX: Construction Industry Institute, University of Texas

CIRIA (1983). *Buildability: An Assessment*, Special Publication 26, London: Construction Industry Research and Information Association.

Dandy, G., Daniell, T., Foley, B., & Warner, R. (2018). *Planning and Design of Engineering Systems*. Boca Raton, FL: CRC Press

Dieter, G. E., & Schmidt, L. C. (2012). *Engineering Design* (5th ed.). New York: McGraw-Hill Higher Education.

DIN 8593 Manufacturing processes joining, Standard by Deutsches Institut Fur Normung E.V. (German National Standard), 09/01/2003

Dorst, K. (2004). On the problem of design problems - Problem solving and design expertise. *Journal of Design Research*, 4(2)

Eekhout, M. (2008). *Methodology for Product Development in Architecture*. NL: Ios Press

Emmitt, S., Olie, J., & Schmid, P. (2004). *Principles of Architectural Detailing*. Blackwell Publishing Ltd

Firesmith, D. (2015). *Open System Architectures: When and Where to be Closed.* Retrieved from https://insights.sei.cmu.edu/sei_blog/2015/10/open-system-architecture-when-and-where-to-be-closed.html

Fox, S., Marsh, L., & Cockerham, G. (2001). Design for manufacture: a strategy for successful application to buildings. *Construction Management and Economics*, 19(5), 493-502. doi:10.1080/01446190110044861

Gerth, R., Boqvist, A., Bjelkemyr, M., & Lindberg, B. (2013). Design for construction: utilizing production experiences in development. *Construction Management and Economics*, 31:2, 135-150. doi:10.1080/01446193.2012.756142

Gosztonyi, S. (2015). Adaptive Façade – which criteria are needed? In Pottgiesser, U., Hemmerling, M. & Böke, J. (Eds.), proceedings of *Façade 2015 Computational Optimisation*. Sweden, Europe: HS OWL, Detmolder Schule für Architektur und Innenarchitektur.

Gowri, K. (1990). *Knowledge-based system approach to building envelope design* (Doctoral dissertation). Concordia University. Available from: BASE, Ipswich, MA.

Han, Y. H., & Lee, K. (2006). A case-based framework for reuse of previous design concepts in conceptual synthesis of mechanisms. *Computers in Industry*, 57(4),305-318. doi:10.1016/j.compind.2005.09.005

Ichida, T., & Voigt, E. C. (1996). *Product Design Review: A Method for Error-Free Product Development*. Portland, Or: Productivity Press.

Jahan, A., Edwards K.L., & Bahraminasab, M. (2016). *Multi-Criteria Decision Analysis For Supporting The Selection Of Engineering Materials In Product Design.* Oxford, UK; Cambridge, MA: Butterworth-Heinemann, an imprint of Elsevier

Jensen, P. (2014). *Configuration of platform architectures in construction* (Doctoral dissertation). Sweden, Europe: Luleå tekniska universitet, Byggkonstruktion och -produktion

Jones, J. C. (1992). *Design Methods* (2. bs. ed.). New York: Van Nostrand Reinhold.

Juvinall, R. C., & Marshek K.M. (2012). Fundamentals of Machine Component Design. Hoboken, NJ: John Wiley & Sons.

Klein, T. (2013) *Integral Facade Construction-Towards a new product architecture for curtain walls* (Doctoral dissertation). Delft Technical University, Delft 2013.

Kolarevic, B. (2015). Towards architecture of change. In Kolarevic, B. & Parlac V. (Eds.), *Building Dynamics: Exploring Architecture of Change,*1-17, New York: Routledge

Koren, Y., Hu, S. J., Peihua G., & Shpitalni, M. (2013). Open-architecture products. *CIRP Annals*, 62(2), 719-729, ISSN 0007-8506

Lawson, B. R. (1970). Open and closed ended problem solving in architectural design. In Honikman (Eds.), 1971. A.P. 1970 Conference, London: RIBA

Leaney P. G., & Wittenberg, G. (1992). Design for assembling: The evaluation methods of Hitachi, Boothroyd and Lucas. *Assembly Automation,* 12(2), 8-17

Lefever, D. D., & Wood, K. L. (1996). Design for assembly techniques in reverse engineering and redesign. *ASME Design Theory and Methodology Conference.* Retrieved from *https://www.sutd.edu.sg/cmsresource/idc/papers/1996-_Design_for_Assembly_Techniques_in_Reverse_Engineering_and_Redesign-DFA-sop_force_flow.pdf*

Li, Z. S., Kou, F. H., Cheng, X. C., & Wang, T. (2006). Model-based product redesign. *International Journal of Computer Science and Network Security*, 6(1).

Liu, T.H., & Fischer, G.W. (1994). Assembly evaluation method for PDES/STEP-based mechanical systems. *Journal of Design and Manufacture*, 4, 1-19.

Loonen, R.C.G.M. (2013). *Climate adaptive building shells*. Retrieved from http://pinterest.com/CABSoverview/

Loonen, R.C.G.M., Favoino, F., Hensen, J.L.M., & Overend, M. (2017). Review of current status, requirements and opportunities for building performance simulation of adaptive facades. *Journal of Building Performance Simulation*, 10:2, 205-223

Loonen, R.C.G.M., Trcka, M., Cóstola, D., & Hensen J.L.M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 25, 483–493, doi:https://doi.org/10.1016/j.rser.2013.04.016

Loonen, R.C.G.M., Rico-Martinez J.M., Favoino F., Brzezicki, M., Menezo, C., La Ferla G., & Aelenei, L. (2015). Design for façade adaptability – Towards a unified and systematic characterization. Proc. *10th Energy Forum - Advanced Building Skins*, Bern, Switzerland, 1274–84.

Lucchetta, G., Bariani, P. F., & Knight, W. A. (2005). Integrated design analysis for product simplification. *CIRP Annals - Manufacturing Technology*, 54(1), 147-150.

Mann, D., & Cathain, C. (2005). Using TRIZ in Architecture: First Steps. *The Triz Journal,* Retrieved from http://triz-journal.com/using-triz-architecture-first-steps/

Meagher, M. (2015). Designing for change: The poetic potential of responsive architecture. *Frontiers of Architectural Research,* 4(2), 159-165.

Molloy, O., Warman, E. A., & Tilley, S. (2012*). Design for Manufacturing and Assembly: Concepts, architectures and implementation.* Springer Science & Business Media.

Natee, S., Low, S. P., & Teo, E. A. (2016). *Quality Function Deployment for Buildable and Sustainable Construction*. Singapore: Springer.

O'Connor, J. T., Rusch, S. E., & Schulz, M. J. (1987), Constructability concepts for engineering and procurement. *Journal of Construction Engineering and Management*, 113(2), 235-248.

Ogwezi, B., Bonser, R., Cook, G, & Sakula, J. (2011). Multifunctional, Adaptable Facades. *TSBE EngD Conference*, TSBE Centre, University of Reading, Whiteknights, RG6 6AF, 5th July 2011.

Oliveira, L. A., & Melhado, S. B. (2011). Conceptual Model for the Integrated Design of Building Façades. *Architectural Engineering & Design Management,* 7(3), 190-204.

Ong, S. K., Nee, A. C., & Xu, Q. L. (2008). *Design Reuse in Product Development Modeling, Analysis and Optimization*. Hackensack, NJ: World Scientific.

Otto, K.N. & Wood, K. L. (1998) Product Evolution: A Reverse Engineering and Redesign Methodology. *Research in Engineering Design* 10(4), 226-243.

Pahl, G., Beitz, W., & Wallace, K. (1996). *Engineering Design: A Systematic Approach*. London: Springer.

Pedgley, O. (2007). Capturing and analysing own design activity. *Design Studies*, (5), 463.

Perino, M. & Serra, V. (2015). Switching from static to adaptable and dynamic building envelopes: A paradigm shift for the energy efficiency in buildings. *Journal of Facade Design and Engineering*, 3 (2), 143-163, doi:10.3233/FDE-150039

Roozenburg, N. F. M., & Eekels, J. (1995). Product design: Fundamentals and methods. Chichester: Wiley.

Schittich, C. (ed.), (2005). Schulungsgebäude in Unterschleißheim. *DETAIL Zeitschrift für Architektur- Steel Construction,* German/English Edition 2005(4), 325-330.

Schnädelbach, H. (2010). Adaptive Architecture – A Conceptual Framework, In proceedings of Geelhaar, J., Eckardt, F., Rudolf, B., Zierold, S, & Markert, M. (Eds.), *MediaCity: Interaction of Architecture, Media and Social Phenomena*, Weimar, Germany, 523-555

Schulungsgebäude in Unterschleißheim (2018, January). Retrieved 20 January 2018 from https://inspiration.detail.de/schulungsgebaeude-in-unterschleissheim-107778.html

Schumacher, M., Schaeffer, O., & Vogt, M. (2010). *Move: Architecure In Motion-Dynamic Components and Elements*. Basel; London: Birkhäuser.

Schwede, D., & Störl, E. (2016). System for the analysis and design for disassembly and recycling in the construction industry. *Central Europe towards Sustainable Building Prague 2016 (CESB16)*

Smith, R. E. (2010). *Prefab architecture: a guide to modular design and construction*. Hoboken, N.J.: John Wiley & Sons.

Smith, S., Smith, G., & Shen Y.T. (2012) Redesign for product innovation. *Design Studies*, 33 (2), 160-184, ISSN 0142-694X

Staib, G., Dörrhöfer, A., & Rosenthal, M. J. (2008). *Components and systems: modular construction: design, structure, new technologies*. München: Edition Detail, Institut für internationale Architektur-Dokumentation; Basel/Boston: Birkhäuser.

Struck C., Almeida M. G., Monteiro da Silva S., Mateus R., Lemarchand P., Petrovski A., ... de Wit J. (2015) Adaptive facade systems – review of performance requirements, design approaches, use cases and market needs. *10th Conference on Advanced Building Skins*, 3-4 November, 1254-1264, Bern, Switzerland.

Tatum, C. B. (1987). Improving constructability during conceptual planning, *Journal of Construction Engineering and Management ASCE,* 113(2), 191–207

Tomiyama, T., Gu, P., Jin, Y., Lutters, D., Kind, C., & Kimura, F. (2009). Design methodologies: Industrial and educational applications. *CIRP Annals - Manufacturing Technology*, 58(2), 543-565.

Tooley M.H., & Knovel (2010). *Design Engineering Manual.* (1st ed). Amsterdam; London; Boston: Butterworth-Heinemann.

Ulrich, K. T. (1992). *The role of product architecture in manufacturing firm.* Massachusetts Institute of Technology, Sloan School of Management.

Ulrich, K. T., & Eppinger, S. D. (2012). *Product Design and Development* (5th ed.). New York: McGraw-Hill/Irwin.

Vermaas, P. E. (2014). Design Theories, Models and Their Testing: On the Scientific Status of Design Research. In Chakrabarti A., & Blessing L. T. M. (Eds.), *An Anthology of Theories and Models of Design.* London: Springer

Opportunities and Challenges for Performance Prediction of Dynamic Complex Fenestration Systems (CFS)

Giuseppe De Michele[1*], Roel Loonen[2], Hemshikha Saini[2], Fabio Favoino[3], Stefano Avesani[4], Luca Papaiz[5], Andrea Gasparella[1]

* Corresponding author
1 Free University of Bolzano/Bozen, Faculty of Science and Technology, giuseppe.demichele@eurac.edu
2 Eindhoven University of Technology, Department of the Built Environment
3 Politecnico di Torino, TEBE research group, Department of Energy
4 Eurac Research, Institute for Renewable Energy
5 Glass Advisor

Abstract

This article presents an overview of possibilities and points of attention for modelling the performance of dynamic CFS in building performance simulation software. Following a detailed analysis of the unique requirements that are associated with modelling of CFS, a comparative study of the capabilities in different software implementations is presented. In addition, we present on overview of state-of-the-art approaches to obtain the necessary Bi-directional Scattering Distribution Functions (BSDF), involving experimental characterisation, databases, and component-level ray-tracing approaches. The second part of the paper provides a detailed discussion of a case study of a high reflective lamella system. This case study complements the review with hands-on information from a practical example and highlights the importance of developing models at the right level of complexity, taking into account the type of questions that the simulation intends to answer and the required accuracy level to do so.

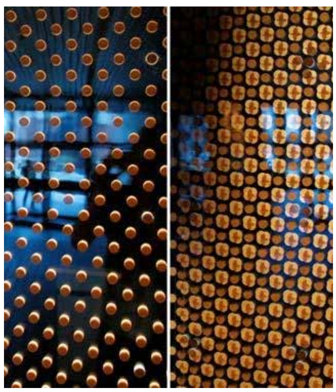
Keywords

Complex Fenestration Systems (CFS), building performance simulation, bi-directional scattering distribution functions, reflective lamella, modelling complexity

DOI 10.7480/jfde.2018.3.2531

1 INTRODUCTION

Contemporary building facades are expected to be increasingly multi-functional. They should not only provide shelter and protection, but often simultaneously also take care of energy conservation, daylight admission, glare prevention, and mitigation of overheating. In response to these high-performance requirements, a growing interest in façades with light redirecting elements, or layers with light scattering properties, can be observed (Appelfeld, McNeil, & Svendsen, 2012; Gong, Kostro, Motamed, & Schueler, 2016; Saini, Loonen, & Hensen, 2018; Vera, Uribe, & Bustamante, 2017). Examples include venetian blinds, glass frits, prismatic films, etc. Unlike conventional glazing, these systems usually exhibit non-specular transmission. Moreover, their transmission properties idiosyncratically depend on the position of the sun or wavelength of the incoming radiation. To distinguish these fenestration systems from specular glazing types, they are often referred to as Complex Fenestration Systems (CFS) (Fig. 1).


a


b


c

FIG. 1 a) Adaptive Fritted Glass, Adaptive Building Initiative *(http://www.hoberman.com/abi.html accessed in May 2018)*; b) IGU Cavity integrated solar shading lamellas *(https://performanceglass.co.uk/pellini-blinds/venetian-blinds/ accessed in May 2018)*; c) Prismatic PCM system, GlassX *(http://glassx.ch/index.php accessed in May 2018)*

The product development of such innovative façade systems can greatly benefit from inputs obtained using building performance simulation tools (Loonen, Singaravel, Trčka, Cóstola, & Hensen, 2014). Such computational tools can also aid in the adoption of CFS in new buildings, by providing opportunities for informed design decision-making from the planning phase itself.

A number of requirements are associated with modelling and simulation of CFS, deriving from their physical characteristics:

- The optical properties of CFS tend to have a high solar angle dependency.
- Many CFS involve scattering/diffusing layers that can be difficult to characterise. Some CFS involve materials (e.g. Phase Changing Materials, PCM) that have a special impact on the heat transfer characteristics of the façade component.
- The three-dimensional shape of optical elements (e.g. lamellas) in CFS can introduce unconventional physical effects.
- CFS are often part of an adaptive façade system, i.e. they can be controlled by varying the component's physical properties to meet different performance requirements. In such situations, it is important to take appropriate façade operation strategies into account in the models (Loonen, Favoino, Hensen, & Overend, 2017).

Because of these considerations, standard simulation workflows might not always provide sufficient flexibility to carry out the task at hand, leading to the need for dedicated models at a higher resolution. When intending to use or develop such detailed models, one should be aware of potential pitfalls and other points of attention. However, in academic literature and software manuals, there is very little attention given to best-practice advice and practical considerations for performance prediction of buildings with CFS.

The objective of this article is, therefore, to compile and present an overview of possibilities and points of attention for modelling the performance of dynamic CFS in building performance simulation tools. Following a detailed analysis of the unique requirements that are associated with modelling of CFS, a comparative study of the capabilities in different software implementations is presented. In addition, we provide an overview of state-of-the-art approaches to obtain the necessary Bi-directional Scattering Distribution Functions (BSDF) for quantification of optical properties of CFS, involving experimental characterisation, databases, and component-level ray-tracing approaches. A case study of a high reflective lamella system is discussed in detail, to complement the review with hands-on information from a practical example.

2 ADVANCED SIMULATION MODELS FOR CFS

2.1 REQUIREMENTS

Due to their intrinsic properties, CFS influence the characteristics of transmitted solar radiation (visible and non-visible). As a result, the main challenges for accurate performance prediction of CFS using building performance simulation (BPS) tools lies in:

- achieving an appropriate representation of two-dimensional angular dependency (on solar geometry and/or control of the components) of optical properties of the fenestration system, such as visible transmittance;
- achieving an appropriate representation of two-dimensional angular dependency (on solar geometry and/or control of the components) of thermal properties of the fenestration system, such as solar heat gain coefficient;
- implementing a control logic (either intrinsic or extrinsic) during the simulation run-time in the case when CFS are part of an adaptive façade system. This is because when façade properties vary over time, the amount of solar radiation that enters the zone also varies, leading to a different thermal response of the space;
- taking into account the interactions between both visual and thermal physical domains to predict the performance of such fenestration elements in an appropriate way.

2.2 DEFINITION OF BSDF DATA

The most commonly-used way of representing the two-dimensional angular dependency of solar properties (transmission and reflection) of CFS is via Bi-directional Scattering Distribution Functions (BSDF). The BSDF method was proposed by Klems (1994) to calculate solar transmission of multi-layered CFS through matrix multiplication. In this method, the front and back hemisphere of the CFS layer is discretised into 145 patches; for each of these, optical properties are specified depending on azimuth and altitude angles. The BSDF dataset-containing file describes the transmission (Bi-directional Transmission Distribution Function, BTDF) and reflection (Bi-directional Reflectance Distribution Function, BRDF) properties of a complex glazing system by a 145 x 145 matrix, according to incident and outgoing angles using Klems' angle basis (Fig. 2).

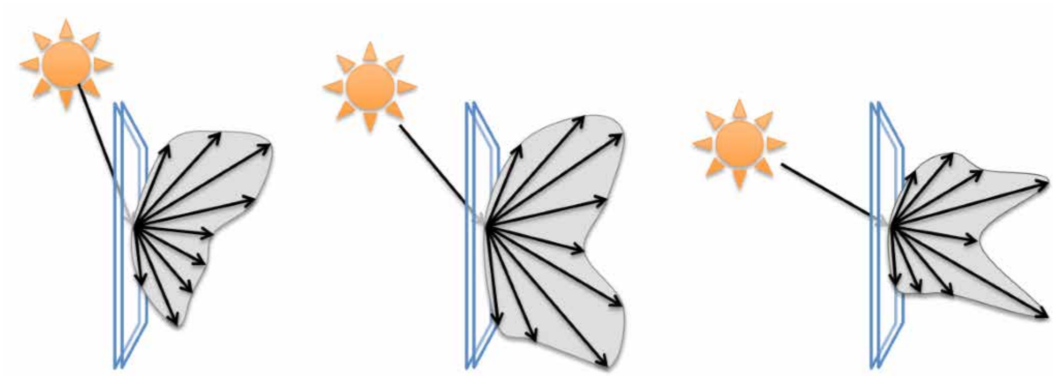


FIG. 2 A BSDF file describes the directional transmission and reflection for many different combinations of ingoing and outgoing directions. *(Image by Christian Kohler, LBNL)*

2.3 REVIEW OF MODELLING OF CFS IN BPS TOOLS

Generally, BPS tools only offer the possibility of considering one domain at a time, either thermal or visual.

As far as BPS tools that allow the evaluation of whole building energy performance by means of thermal networks (i.e. Energy Plus, TRNSYS, ESP-r, etc.) are concerned, the main practice, while considering the thermal and optical properties of a complex fenestration system, is to use calculation algorithms according to ISO 15099 for the layer-by-layer heat transfer. In the ISO 15099 standard, the analytical algorithms for the optical modelling are restricted to simplified models, developed for planar or curved blinds that behave as ideal diffusers. For this reason, the algorithm relative to the optical modelling has been fully replaced with BSDF data in most of these BPS tools:

1 EnergyPlus: Since version 7.2, the BSDF functionality has been part of EnergyPlus as one of the optical representations of fenestration systems. This implementation relies on the strong integration between EnergyPlus and Berkeley Lab WINDOW (or WINDOW) (Berkeley Lab, 2007) software that allows the export/import of .idf files. The Construction:ComplexFenestrationState (US Department of Energy, 2010) can be controlled during simulation run-time, by making use of the EMS (Energy Management System) functionality. Additionally, EnergyPlus offers the possibility to define specific external schedules for solar transmission and solar absorption of CFS. In recent work, Hoffmann, Lee, & Clavero (2014) used this approach for pre-calculating the two schedules, for different shading systems, by using Radiance. The BSDF function is also integrated in COMFEN, a user-friendly interface to the EnergyPlus/Radiance engines.

2 ESP-r: ESP-r is the only tool with an in-house developed model for complex fenestration systems, based on the AGSL shading model; not BSDF. It is aptly named the CFS functionality (Lomanowski & Wright, 2012)the Complex Fenestration Construction (CFC. Alternate property sets for different fenestration/shading states can easily be changed using TMC control or the BCVTB-ESP-r control functionality (Hoes, Loonen, Trčka, & Hensen, 2012). An alternative approach called the "black-box model" was developed by Kuhn, Herkel, Frontini, Strachan, & Kokogiannakis (2011), who proposed a new methodology for the evaluation of solar transmission of the complex system. This approach simplifies the modelling part and does not require many measurements. The model takes as input measured or analytically derived total solar energy transmittance (gtot), total solar transmittance (te tot), and total solar reflectance (re tot) for different angles of incidence. Then, the model introduces the radiant and convective effect of solar heat gains into the energy balance of the building through a two-layer approach. Other applications of the model are reported in (Frontini, Kuhn, Herkel, Strachan, & Kokogiannakis, 2009).

3 Fener: Fener is a dedicated tool that was developed to ease the modelling and simulation of CFS systems (Bueno, Wienold, Katsifaraki, & Kuhn, 2015). It combines Radiance with a reduced-order RC network approach for thermal calculations on a time step basis. One of the specific strengths of Fener is its flexibility for implementing shading control algorithms, based on, for example, daylighting variables such as illuminance and glare, thermal variables such as indoor temperature and energy load, or weather variables such as wind and solar radiation.

4 TRSNSYS: A new TRNSYS type for daylight performance prediction with BSDF systems has recently been developed at Eurac Research (TypeDLT) (De Michele, Filippi Oberegger, & Baglivo, 2015). These daylight predictions can be coupled with the multi-zone thermal model (Type 56). Since version 18, bi-directional thermal properties, according to ISO 15099, can also be calculated in TRNSYS's thermal building model (Hiller & Schöttl, 2014).

The main and most accurate BPS tool that allows evaluation of the performance of the built environment in the visual physical domain (adopted as a calculation engine in many interface softwares) is Radiance (Ward, 1989). In particular, the multi-phase matrix-based methods (e.g. three-phase and five-phase) are useful in the present context, because of the possibility for annual evaluations (Subramaniam, 2017). All the matrix methods use common input data to describe the light passing through the CFS, which is the BSDF. Differently from the thermal analysis, in the daylighting analysis it is also possible to employ high resolution BSDF (tensor tree resolution) mainly for glare analysis and the calculation of the Annual Sunlight Exposure (ASE) index (IES, 2012).

3 SOURCES OF BSDF DATA

3.1 COMPLEX GLAZING DATABASE

BSDF files (in XML format) for a variety of window materials and daylighting systems can be obtained from the LBNL complex glazing database (CGDB). This resource contains more than 100 systems, such as shading devices and materials (e.g., venetian blinds, roller shades, drapes, cellular shades, shade fabrics, etc.), light redirecting materials (e.g., prismatic films, etc.) and scattering glazing (e.g., diffuse glass, glazing frits, decorative glass, etc.). With this database, customised multi-layer glazing systems for different configurations of a façade system (e.g. shades up, down, and/or tilted) can be created using the Berkeley Lab WINDOW program. From this program, data files can be exported for use in a number of whole building performance simulation programs.

Especially when innovative fenestration systems are considered, it may happen that the optical behaviour of the fenestration system is not yet available in the CGDB. In this scenario, two options are available to obtain the necessary bi-directional optical data: i) experimental characterisation or ii) modelling/simulation.

3.2 MEASUREMENTS

Photometric equipment, such as a goniophotometer, is needed to characterise the angular transmission and reflection properties. This equipment is available in only a few research labs around the world. Experimental characterisation is practically possible for small-scale CFS with homogenous scattering properties.

3.3 SIMULATIONS

For macro-scale CFS with complex geometry e.g. louvres and specular blinds, the incident light source of photometric equipment cannot sufficiently take into account variations in CFS. BSDF files for such systems can be created by applying radiosity or ray-tracing algorithms on a geometrical model of the shading system or daylighting device in WINDOW or TracePro/genBSDF, respectively. For a simplified geometrical model and Lambertian systems, WINDOW can be used, while for complex geometries and/or non-Lambertian surfaces, TracePro or genBSDF should be used. TracePro is a commercial software with a 3D CAD-based graphical user interface for design and analysis of optical and illumination systems. genBSDF, part of the Radiance daylight simulation suite, is a free and open source tool that generates a BSDF file from a Radiance or MGF scene description (McNeil, Jonsson, Appelfeld, Ward, & Lee, 2013).

3.4 COMBINE MEASUREMENT AND SIMULATIONS

It is possible to extend the simulation method with detailed measured data of the shading material. For this specific application, the opaque material reflectance can be characterised either through a spectral curve (Fig. 3 a) or BRDF (Figs. 3 b and c). The spectral curve method is a hemispherical measure of the material reflection, which is reliable for materials that behave or can be assumed as Lambertian; while the BRDF is suitable for materials whose reflection presents complex behaviour (e.g. high reflective or retro-reflective material) and an angular distribution is required.

In order to use the spectral data within WINDOW and Radiance, it has to be integrated on the solar and visible ranges. The integrated values are directly set in the WINDOW material library, while in Radiance, they are adopted by using the plastic material. Then, the material has to be applied to a geometry that represents the shading device. Regarding the BRDF, such data can be used in Radiance by applying the BSDF material to a 3D geometry using genBSDF to generate an xml file of the shading device. This xml file can then be imported in WINDOW as a shading layer where it can be directly joined to the glass layers in order to generate the BSDF of the whole system.

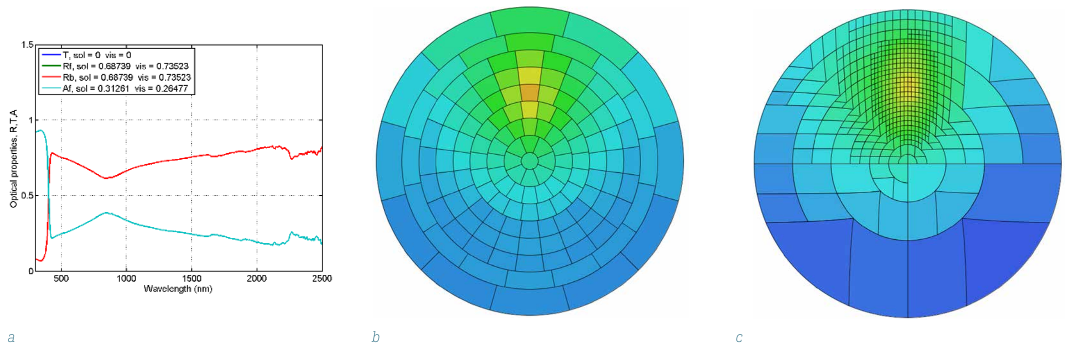


FIG. 3 a) is an example of spectral reflection curves of an opaque white material; b) and c) are two measured BRDF respectively on Klems and tensor-tree base.

4 PERFORMANCES EVALUATION OF HIGHLY REFLECTIVE LAMELLAS

In this section, the modelling and simulation of a CFS is presented. The shading system is a curved lamella characterised by a highly reflective coating. In order to show the impact of correct modelling of the shading system on the energy and daylighting results, two models of the same shading system are compared.

4.1 MODELLING OF THE SHADING SYSTEM

The shading device is a curved commercial blind produced by Pellini ScreenLine®. The blind is coated with a highly reflective layer. Two fixed shading configurations with 15° and 30° blind tilt angles have been considered in these simulations. Geometrical dimensions are reported in Fig. 4 and Table 1.

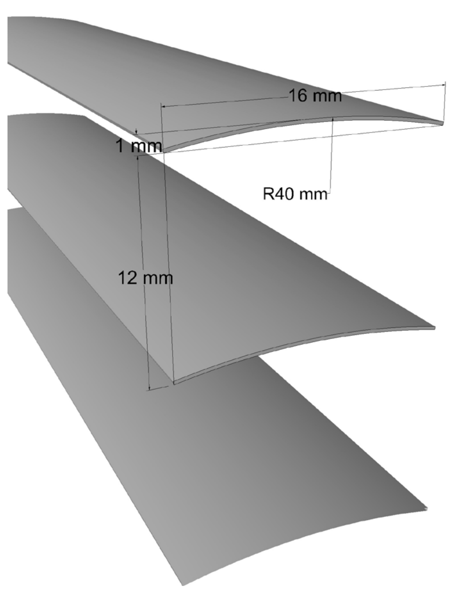


FIG. 4 3D geometry of blind

Blind width	16	mm
Blind thickness	0.2	mm
Pitch	12	mm
Blind tilting	15 - 30	°
Raise	1	mm

TABLE 1 Blind dimensions

The configuration of the two blinds has been modelled using both simplified and detailed approaches.

Simplified approach. The shading model was completely generated within the Berkeley Lab WINDOW software. The coating behaviour was assumed as Lambertian in order to use the material definition of WINDOW. In particular, the measured spectral data of the coating have been imported into WINDOW as shade materials. Table 2 shows the integrated reflectance values of the coating and the emissivity used as material for the blinds. The blind geometry has been precisely reproduced using the built-in functionality of WINDOW to generate custom horizontal venetian blinds; Fig. 5 shows the lamellas' definition within the *Shading Layer Library*.

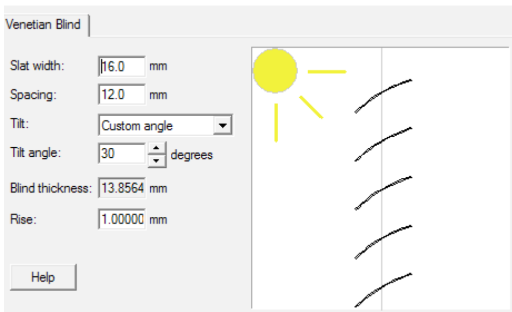


FIG. 5 Blinds geometry in WINDOW

Conductance	100 W/m k
Thickness	0.2 mm
Integrated values	
Solar Reflectance Front	0.901
Solar Reflectance Back	0.840
Visual Reflectance Front	0.959
Visual Reflectance Back	0.823
Emissivity Front	0.150
Emissivity Back	0.450

TABLE 2 Coating characterisation within WINDOW

Detailed approach. The shading modelling is performed using angular measured data and Radiance. The highly reflective coating has been characterised by means of measured angular reflectance values (BRDF) for Visible and Near Infrared wavelengths. The BRDFs were applied as material to the 3D geometry of the blinds within Radiance. The function genBSDF was then used to describe the geometry of the shade and its complex coating in the form of BSDF, with Klems resolution, for solar and visible spectrum. Additionally, a third BSDF for the infrared (IR) wavelength was created using the *plastic* material of Radiance and assuming as coefficient of reflection the complement to 1 of the emissivity front and back in Table 2. This last step was required in order to evaluate the hemispherical emissivity front and back and the infrared transmission of the system. Finally, an XML file that collects all the previous information was generated and imported into WINDOW.

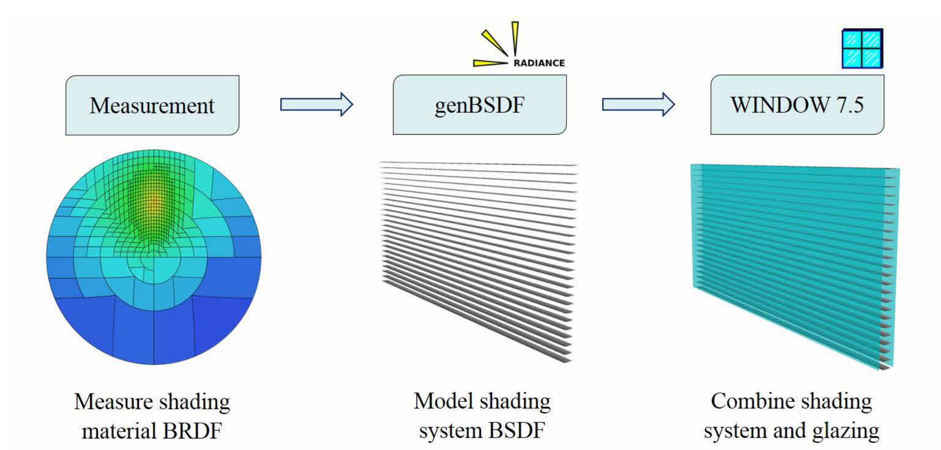


FIG. 6 Workflow of the detailed modelling procedure of the shading system

The shade models were then coupled with the glass layers within WINDOW in order to compose the complete system (Fig. 6). The fenestration consists of a triple-pane insulating glazing (8-29-6-16-8.8). Glass layers 1 and 2 are monolithic float glass, while layer 3 is laminated float glass; their sizes and thermal properties are listed in Table 3. On faces 3 and 5, a low-emissivity coating is placed. The cavities are filled with a gas mixture containing 90% argon and 10% air. The thermal and optical characteristics of the glazing system are: U-value 0.72 W/m2 K, SHGC 0.527 and visible transmission 0.6. The shading system is located in the first cavity, 29 mm. No window frame is considered.

PROPERTY	GLASS1	GLASS2	GLASS3
Thickness (mm)	8.0	6.0	8.8
Solar transmittance	0.797	0.618	0.573
Solar reflectance front	0.074	0.247	0.245
Solar reflectance back	0.074	0.186	0.137
Visual transmittance	0.892	0.893	0.882
Visual reflectance front	0.082	0.044	0.043
Visual reflectance back	0.082	0.048	0.048
IR transmittance	0.000	0.000	0.000
Emissivity front	0.837	0.037	0.037
Emissivity back	0.837	0.837	0.837
Conductivity	1.000	1.000	0.757

TABLE 3 Thermal and optical properties of glazing panes

4.2 IMPACT AT FAÇADE LEVEL: SIMPLE PROCEDURE AGAINST ADVANCED CHARACTERISATION

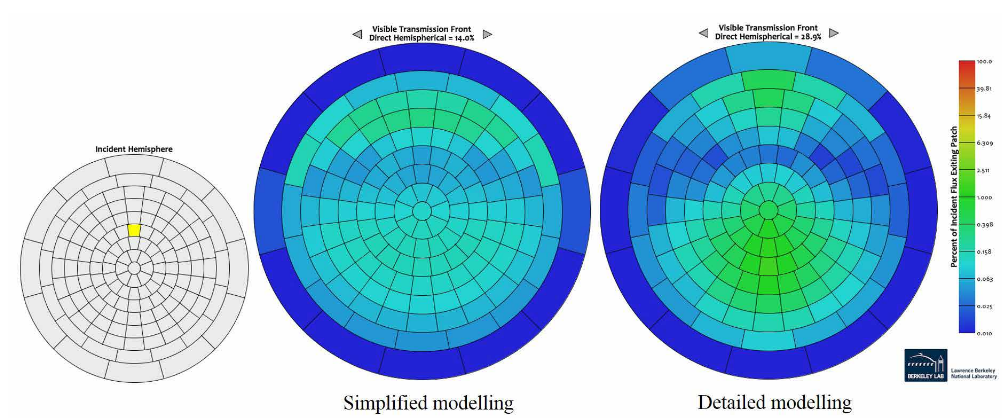


FIG. 7 BSDFs Visible Transmission Front for the fenestration system with blind titled at 15°. The graphs show the 145 outgoing values of visible transmission for an incident ray normal to the system and at 30° of elevation (yellow patch on the first left image).

A first comparison can be done by observing the differences between the angular visible transmission of the CFS in Fig. 7. In particular, the case with blinds tilted at 15° with an incident ray of azimuth angle 0° and elevation angle of 30° is shown. The difference between the models is evident; the detailed approach is able to reproduce the inter-reflections that occur between the blinds due to the high reflectivity of the coating. The angular transmission values are higher, green and yellow patches in the right graph of Fig. 7, compared to the simplified model, which underestimates the light transmission. In fact, the hemispherical front transmission values are very different: 35% for the detailed model against 17.6% for the simplified model. Similar behaviour has been found for other incident angles and blind configurations.

Another relevant consideration can be made, based on the angular Solar Heat Gain Coefficient (SHGC). Fig. 8 shows the SHGC values for 145 incident angles, for the cases analysed. Looking at the polar graphs, it can be observed that in general the detailed model has greater values of SHGC in the upper part of the hemisphere compared to the simple model. Therefore, the simple model will underestimate the solar gain in the thermal simulation.

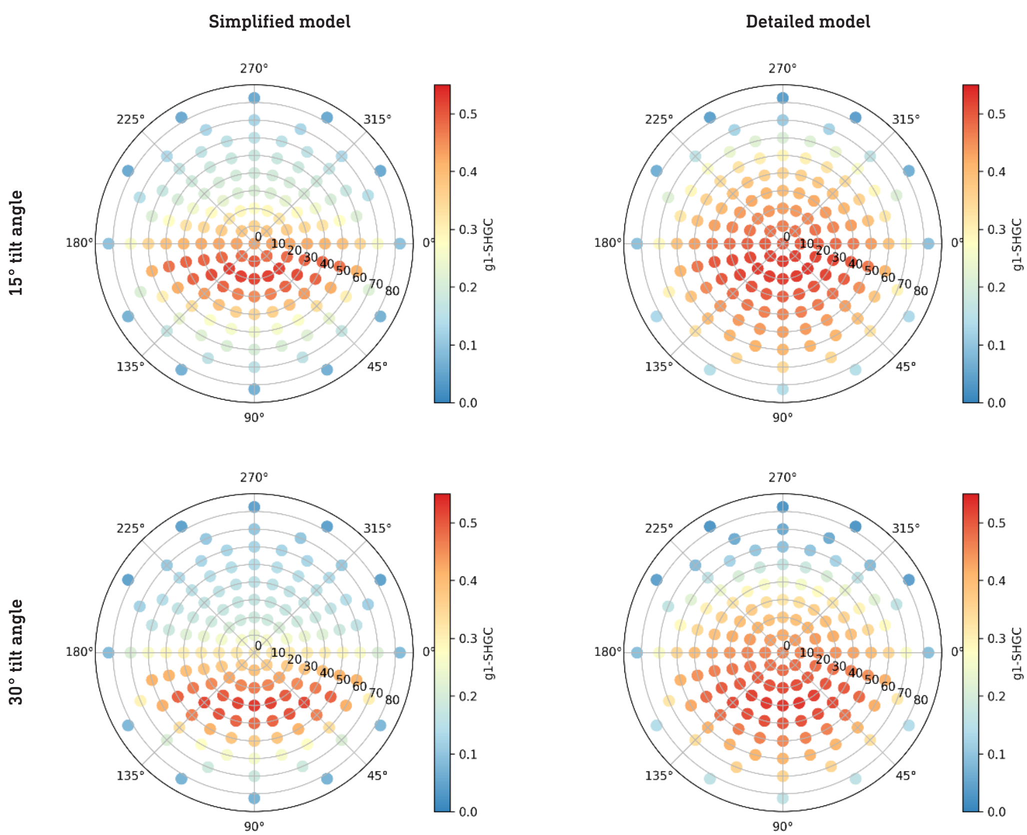


FIG. 8 Angular dependent SHGC

4.3 IMPACT ON REFERENCE ROOM: SIMPLE PROCEDURE AGAINST ADVANCED CHARACTERISATION

The previous paragraph has reported the differences between the simplified and detailed approach at the façade level. In this part, the two modelling approaches for CFS have been evaluated at a reference room level, using TRNSYS18 with the new CFS module based on ISO 15099 for the energy part, and the Daylighting Coefficient Method of Radiance for the daylighting analysis. The model used is a single zone of dimensions 3.3 m x 8 m x 2.7 m, located in Bolzano (46.467° N and 11.33° E), Italy. The zone consists of a south facing external façade with a window-to-wall ratio (WWR) of 50% (Fig. 9). In order to underline the effect of the façade on the energy balance, all the surfaces are assumed adiabatic except for the south-façade, and internal gains are not considered.

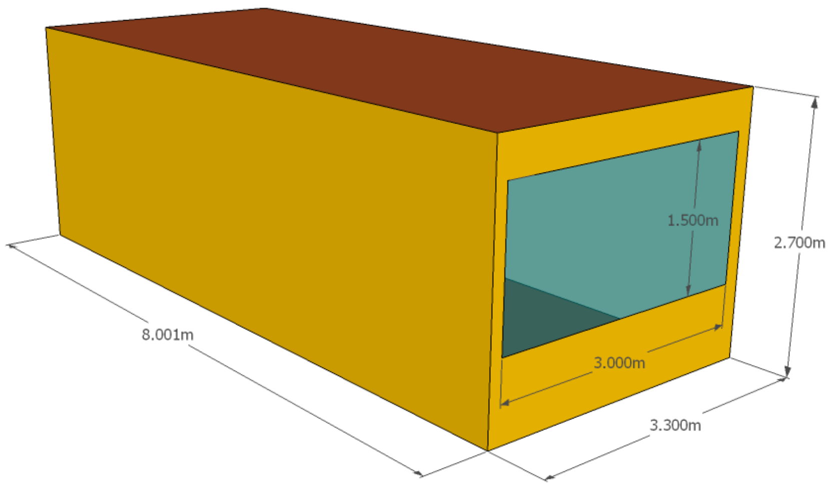


FIG. 9 3D model and main dimensions of the zone

The opaque element transmittance and reflectance are reported in Table 4. The set point for cooling is 20 °C, while for heating it is 26 °C. The heating and cooling system has unlimited power and is always on. Infiltration is always set to 0.40 ACH. The daylight availability is calculated over a grid located at 0.8 m from the floor and with a resolution of 0.5x0.5 m.

SURFACE	U [W/M^2 K]	REFLECTANCE
Wall	0.51	0.50
Roof/Ceiling	0.32	0.85
Floor	0.39	0.25
Ground	-	0.20

TABLE 4 Thermal and optical characteristics of the opaque elements

Results are reported for the two cases analysed, blinds always deployed at 15° and at 30° tilt angle. The comparison between simplified and detailed modelling is done on the annual ideal energy load and annual daylight distribution.

A / 15° tilt angle			B / 30° tilt angle		
	Heating [kWh/m2y]	Cooling [kWh/m2y]		Heating [kWh/m2y]	Cooling [kWh/m2y]
Simplified	13.1	10.1	Simplified	17.1	7.4
Detailed	7.1	21.1	Detailed	8.6	12.6
Difference	-46%	108%	Difference	-50%	69%

TABLE 5 Ideal heating and cooling demand for shadings deployed at 15° (A) and 30° (B)

Table 5 shows ideal heating and cooling load for the two blind tilt angles. The differences between simplified and detailed are relevant in both cases, especially for the cooling demand with blinds at 15°, where the difference rises to 108% (Table 5A). The detailed model considers the effective reflection of the material blind and then it accounts for a higher solar gain as also shown in the images in Fig. 8. Both in summer and winter seasons, the solar gains through the detailed model are higher than the simplified model. In fact, the heating demand is overestimated by 46%. Similar trends are found for the lamellas at 30°. The cooling difference is reduced to 70% since the more closed position of the blinds reflect more energy when the sun is around the solstice period.
The difference in heating load is slightly higher (50%) because the detailed model accounts for the inter-reflected direct radiation, which is more relevant for the 30° tilt angle case.

A / 15° tilt angle			
	Simplified	Detailed	Difference
UDI-n	19.1	17.5	-8%
UDI-s	26.5	24.1	-9%
UDI-a	48.2	46.9	-3%
UDI-x	6.2	11.5	85%
DA_300	54.5	58.5	7%
sDA_300/50	58.3	62.5	7%

B / 30° tilt angle			
	Simplified	Detailed	Difference
UDI-n	24.4	19	-22%
UDI-s	28.3	23.7	-16%
UDI-a	44.6	49.2	10%
UDI-x	2.7	8.2	204%
DA_300	47.3	57.3	21%
sDA_300/50	62.8	71.8	14%

TABLE 6 Daylighting indicators for shadings deployed at 15° (A) and 30° (B). Values are averaged over the sensor grid.

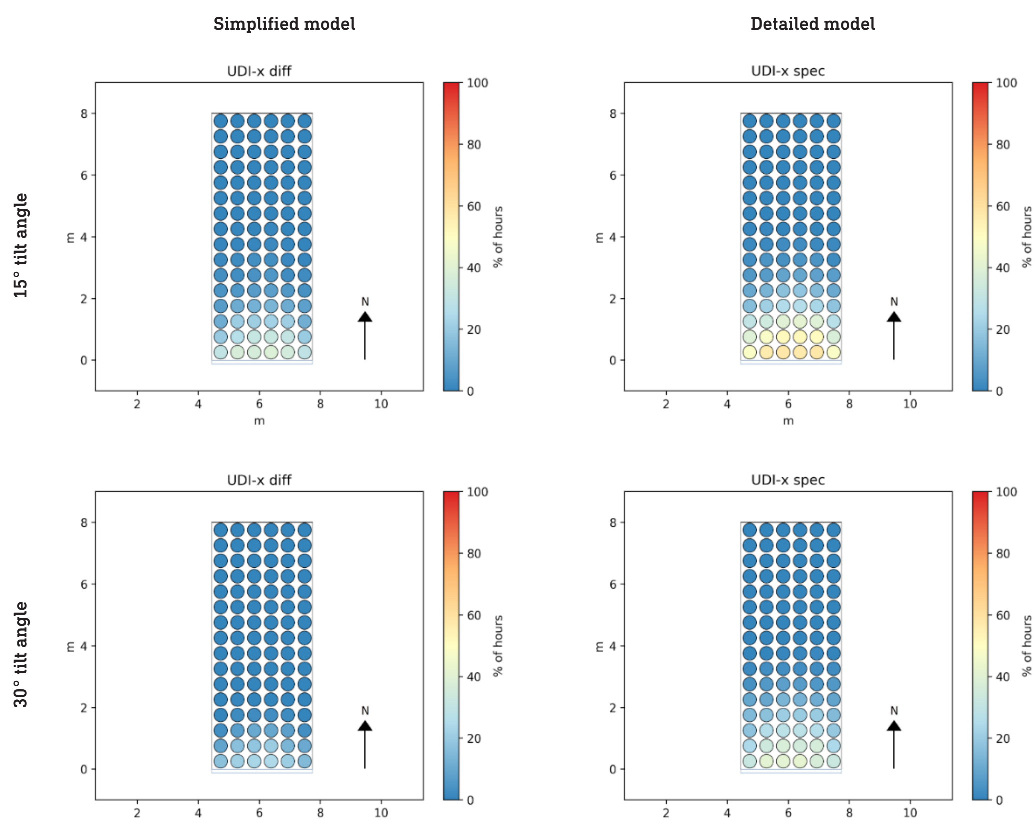


FIG. 10 UDI-exceed (Illuminance > 3000 lux) distribution over the sensors grid

Table 6 shows the average sensor grid values of selected annual daylighting indices for the two cases. The indicators used for the comparison are Useful Daylight Illuminance (UDI) (Mardaljevic & Nabil, 2005), Daylight Autonomy (DA) and spatial Daylight Autonomy (sDA) (Reinhart, Mardaljevic, & Rogers, 2006). For the latter two indices, the illuminance threshold was set to 300 lux. Regarding the daylighting results, the main differences were found for the case with 30° tilting. This is explained by the fact that the more the blinds are closed, the greater is the influence of the inter-reflection caused by the specularity of the blind coating. In particular, the simple model underestimates the percentage of hours in which the illuminance values exceed the 3000 lux (UDI-x) of the 204%. Additionally, in the case of 15° tilt, the greater difference is for the UDI-x, 85%. The main differences are related to the UDI-x, also because this index is primarily evaluated on the sensors close to the window (Fig. 10), and then close to influence of the shading system.

In general, the trend agrees with the expectation; the detailed model reduces the indices of illuminance below a threshold value (i.e. UDI-n and UDI-s, illuminance values below 100 lux, and between 100 and 300 lux respectively) from 8% to 22% for the cases with 15° tilt and 30° tilt respectively, while increasing the indicators of illuminance higher than a threshold (i.e. DA, sDA), from 7% to 21%. This result clearly shows that the detailed model allows for a major quantity of light entering the space.

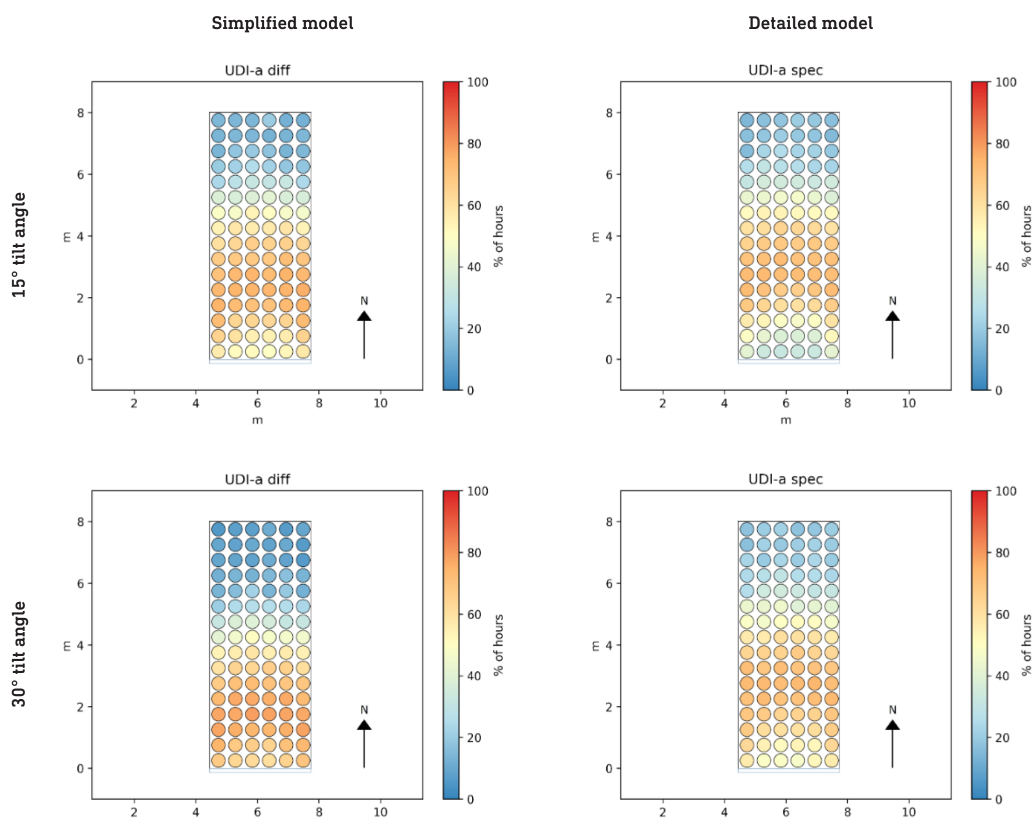


FIG. 11 UDI-autonomous (300 lux < Illuminance < 3000 lux) distribution over the sensors grid

Another important consideration concerns the UDI-a (i.e. illuminance level between 300 lux and 3000 lux). In both cases, the difference related to this index is small (-3% and 10%), but looking at the UDI-a distribution over the grid in Fig. 11, the distribution of the highest UDI-a values, for the detailed model, shifts almost one metre inside the room. This means that with the detailed model the light penetrates deeper into the room, and that the simple model would not be able to highlight this effect.

5 CONCLUSIONS

This article has reviewed several challenges and opportunities of modelling the performance of CFS in building simulation software. First, the unique simulation requirements were identified in terms of physical phenomena and the intended purpose of the simulation task. Then, a detailed overview of CFS models in state-of-the-art BPS tools was given, complemented by a description of bi-directional scattering distribution functions, and how such input data can be obtained. The second part of the article has demonstrated these concepts in a practical case study with a highly-reflective lamella system. The main take-home message of the case study relates to the complexity level of the simulation models, showing that this should always be carefully chosen with respect to the characteristics of fenestration system and the type of questions the simulation study should address.

Acknowledgements
This study has been developed in the framework of the research activities of the project FACEcamp n. ITAT1039, funded by European Regional Development Fund and Interreg ITA AUT programme. Thanks to Pellini SpA for the support providing technical information and detailed measurements of their shading system.

References

Appelfeld, D., McNeil, A., & Svendsen, S. (2012). An hourly based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems. *Energy and Buildings*, *50*, pp.166–176. http://doi.org/10.1016/j.enbuild.2012.03.038

Berkeley Lab. (2007). *LBNL WINDOW 7*. Retrieved from http://windows.lbl.gov/software/window/window.html

Bueno, B., Wienold, J., Katsifaraki, A., & Kuhn, T. E. (2015). Fener: A Radiance-based modelling approach to assess the thermal and daylighting performance of complex fenestration systems in office spaces. *Energy and Buildings*, *94*, pp.10–20. http://doi.org/10.1016/j.enbuild.2015.02.038

De Michele, G., Filippi Oberegger, U., & Baglivo, L. (2015). Coupling dynamic energy and daylighting simulations for complex fenestration systems. In *Building Simulation Applications 2015 - 2nd IBPSA-Italy Conference*. Bolzano-Bozen.

Frontini, F., Kuhn, T. E., Herkel, S., Strachan, P., & Kokogiannakis, G. (2009). Implementation and application of a new bi-directional solar modelling method for complex facades within the ESP-r building simulation program. *Eleventh International IBPSA Conference*,pp.936–943. Retrieved from http://ibpsa.org/proceedings/BS2009/BS09_0928_935.pdf

Gong, J., Kostro, A., Motamed, A., & Schueler, A. (2016). Potential advantages of a multifunctional complex fenestration system with embedded micro-mirrors in daylighting. *Solar Energy*, *139*, pp.412–425. http://doi.org/10.1016/j.solener.2016.10.012

Hiller, M., & Schöttl, P. (2014). MODELLIERUNG KOMPLEXER VERGLASUNGSSYSTEME IN TRNSYS. *BauSim* pp. 387–394.

Hoes, P., Loonen, R. C. G. M., Trčka, M., & Hensen, J. L. M. (2012). Performance prediction of advanced building controls in the design phase using ESP-r, BCVTB and Matlab. In *Proceedings of Building Simulation and Optimization*. Loughborough, UK.

Hoffmann, S., Lee, E. S., & Clavero, C. (2014). Examination of the technical potential of near-infrared switching thermochromic windows for commercial building applications. *Solar Energy Materials and Solar Cells*, *123*, pp.65–80. http://doi.org/10.1016/j.solmat.2013.12.017

IES, I. E. S. (2012). *Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*.

ISO 15099:2003: (2003). *Thermal performance of windows, doors and shading devices — Detailed calculations*.

Klems, J. H. (1994). A new method for predicting the solar heat gain of complex fenestration systems - II. Detailed description of the matrix layer calculation. *ASHRAE Transactions*, *100*(1), pp.1065–1072. http://doi.org/citeulike-article-id:10521068

Kuhn, T. E., Herkel, S., Frontini, F., Strachan, P., & Kokogiannakis, G. (2011). Solar control: A general method for modelling of solar gains through complex facades in building simulation programs. *Energy and Buildings*, *43*(1), pp.19–27. http://doi.org/10.1016/j.enbuild.2010.07.015

Lomanowski, B. A., & Wright, J. L. (2012). The Complex Fenestration Construction: a practical approach for modelling windows with shading devices in ESP-r. *Journal of Building Performance Simulation*, *5*(January), pp.185–198. http://doi.org/10.1080/19401493.2011.552735

Loonen, R. C. G. M., Favoino, F., Hensen, J. L. M., & Overend, M. (2017). Review of current status, requirements and opportunities for building performance simulation of adaptive facades†. *Journal of Building Performance Simulation*, *10*(2). http://doi.org/10.1080/19401493.2016.1152303

Loonen, R. C. G. M., Singaravel, S., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2014). Simulation-based support for product development of innovative building envelope components. *Automation in Construction*, *45*. http://doi.org/10.1016/j.autcon.2014.05.008

Mardaljevic, J., & Nabil, A. (2005). The Useful Daylight Illuminance Paradigm: A Replacement for Daylight Factors. *Lux Europa, Berlin*, pp.169–174.

McNeil, A., Jonsson, C. J., Appelfeld, D., Ward, G., & Lee, E. S. (2013). A validation of a ray-tracing tool used to generate bi-directional scattering distribution functions for complex fenestration systems. *Solar Energy*, *98*(PC), pp.404–414. http://doi.org/10.1016/j.solener.2013.09.032

Reinhart, C. F., Mardaljevic, J., & Rogers, Z. (2006). Dynamic daylight performance metrics for sustainable building design. *LEUKOS - Journal of Illuminating Engineering Society of North America*, *3*(1), pp.7–31. http://doi.org/10.1582/LEUKOS.2006.03.01.001

Saini, H., Loonen, R. C. G. M., & Hensen, J. L. M. (2018). Simulation-based performance prediction of an energy-harvesting façade system with selective daylight transmission. In *Proceedings of ICAE2018 - International Congress on Architectural Envelopes*. San Sebastian, Spain.

Subramaniam, S. (2017). *Daylighting Simulations with Radiance using Matrix-based Methods*. Retrieved from https://radiance-online.org/learning/tutorials/matrix-based-methods

US Department of Energy. (2010). EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations. *US Department of Energy*, (c), pp.1–847. http://doi.org/citeulike-article-id:10579266

Vera, S., Uribe, D., & Bustamante, W. (2017). Optimization of a fixed exterior complex fenestration system considering visual comfort and energy performance criteria. *Building and Environment*, *113*(June), pp.11–14. http://doi.org/10.1016/j.buildenv.2016.07.027

Ward, J, G. (1989). The RADIANCE Lighting Simulation and Rendering System. *21st Annual Conference on Computer Graphics and Interactive Techniques*, pp.459–472. Retrieved from http://radsite.lbl.gov/radiance/papers/sg94.1/Siggraph1994a.pdf

Analysis of Heating Effects and Deformations for a STAF Panel with a Coupled CFD and FEM Simulation Method

Daniel Brandl[1*], Helmut Schober[2], Christoph Hochenauer[1]

* Corresponding author
1 Graz University of Technology/ Institute of Thermal Engineering, Austria, daniel.brandl@tugraz.at
2 Graz University of Technology/ Institute of Building Construction, Austria

Abstract

Conventional sandwich panels are one of the cheapest and easiest solutions for forming the thermal building envelope of industrial buildings. They are pre-fabricated façade elements, of which millions of square metres have been produced and mounted every year. There is great potential to reduce the consumption of fossil fuels and CO2 emissions through the solar thermal activation of such a sandwich panel. In the course of the research project ABS-Network SIAT 125, a Solar Thermal Activated Façade (STAF) panel was designed which is to be optimised both thermally and structurally. This study shows a first version of a so-called 'one way coupled' thermal and structural analysis of a conventional sandwich panel compared to the STAF panel. For this purpose, the numerical methods of Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) are used together in one simulation environment. Furthermore, results from an outdoor test facility are presented where a first version of a STAF panel is tested under real climate conditions. The CFD model was positively evaluated by comparing measured and computed temperatures.

Keywords

Solar Thermal Activated Façade (STAF) Panel, Computational Fluid Dynamics (CFD), Finite Element Method (FEM), outdoor measurements

DOI 10.7480/jfde.2018.3.2567

1 INTRODUCTION OF THE STAF PANEL

1.1 DEVELOPMENT APPROACH

Conventional sandwich panels are some of the cheapest and easiest solutions for forming the thermal building envelope of industrial buildings (BKI 2018). They are pre-fabricated façade elements, of which millions of square metres have been produced and mounted every year (Koschade, 2011; IC Market Tracking, 2016). Sandwich panels consist of both an interior as and exterior metal plate (steel and aluminium are widely used) with thermal insulation (for example expanded polystyrene "EPS" or mineral wool "MW") in between (EN 14509).

The basic idea of the Interreg project "ABS-Network SIAT 125" is the solar thermal activation of a conventional sandwich panel. In this case, thermal activation means the conversion of solar energy to provide energy for the production of domestic hot water and/or heating and cooling applications. Thanks to a functionally convincing and creatively sophisticated revision of sandwich panels, the field of application can be extended to office buildings, residential buildings, buildings for education, etc. In the field of research, studies were more focused on the variation of different compositions as thermal insulation, in order to improve both the static and the thermal behaviours. Authors presented studies using foam core as thermal insulation (Missoum, Lacaze, Amabili, & Alijani, 2017; Qintana & Mower, 2017), honeycomb structure (Ebrahimi, Someh, Norato, & Vaziri, 2018) and different filling materials like aluminium (Li, Zheng, Yu, & Lu, 2017), blockboard and batternboard (Haseli, Layeghi, & Hosseinabadi, 2018), ceramic, silicon, or carbon (Yuan et al., 2018), cellulose (Yazdani Sarvestani, Akbarzadeh, Niknam, & Hermenean, 2018) or even concrete (Hashemi, Razzaghi, Moghadam, & Lourenço, 2018). The approach of using a solar thermally activated sandwich panel has not yet been found in the actual state of the science.

1.2 PRODUCTION CONCEPT AND WORKING PRINCIPLE OF THE STAF-PANEL

The metal sheets of the so-called 'Solar Thermal Activated Façade' (STAF) panel have integrated fluid pipes that can be produced by the so-called 'Roll-Bonding' fabrication method (Eizadjou, Manesh, & Janghorban, 2009). With this special metal-forming technique, two sheets are combined to one steel plate whereby the fluid pipes are produced by inflation (one-sided or double-sided inflation). In the case of the one-sided inflation method, only one metal sheet is deformed, whereas an equilateral deformation is realised in the double-sided inflation method. The exterior plate acts as an absorber of a solar thermal collector for the conversion of solar energy into hot water, whereas the interior plate can be used for heating and cooling of the interior rooms. The company Talum d.d. (Talum, 1942) is using this technology in order to produce absorber plates for evaporators of refrigerators. Fig. 1 shows a photo of a STAF panel which is equipped with double side inflated aluminium absorbers.

The absorbers were produced by Talum d.d. in Kidricevo Slovenia, and the sandwich panel was finalised at the company Brucha Ges.m.b.H. in Michelhausen Austria (Brucha, 1948), where the thermal insulation was filled between the interior and exterior absorber plate. This STAF panel, with dimensions of 1.75 x 0.5 x 0.15m, was used in the outdoor measurements presented in Chapter 2. The actual state of the science reveals a number of studies in which two main applications for roll-bonded plates were found. One application is the use of roll-bond heat exchangers used as evaporators in cooling systems and refrigerators (Ravi, Krishnaiah, Akella, & Azizuddin, 2015;

Hermes, Melo, & Negrão, 2008; Righetti, Zilio, & Longo, 2014), while the other application is the use of a roll-bonded thermal absorber for conversion of solar energy and hot water production (Sun ,Wu, Dai, & Wang, 2014; Del Col, Padovan, Bortolato, Dai Prè, & Zambolin, 2013) or for the cooling of photovoltaic modules in order to improve efficiency (Brötje, Kirchner, & Giovannetti, 2018). Studies concerning roll-bonded absorbers that form a sandwich panel are not yet available in the state of the science.

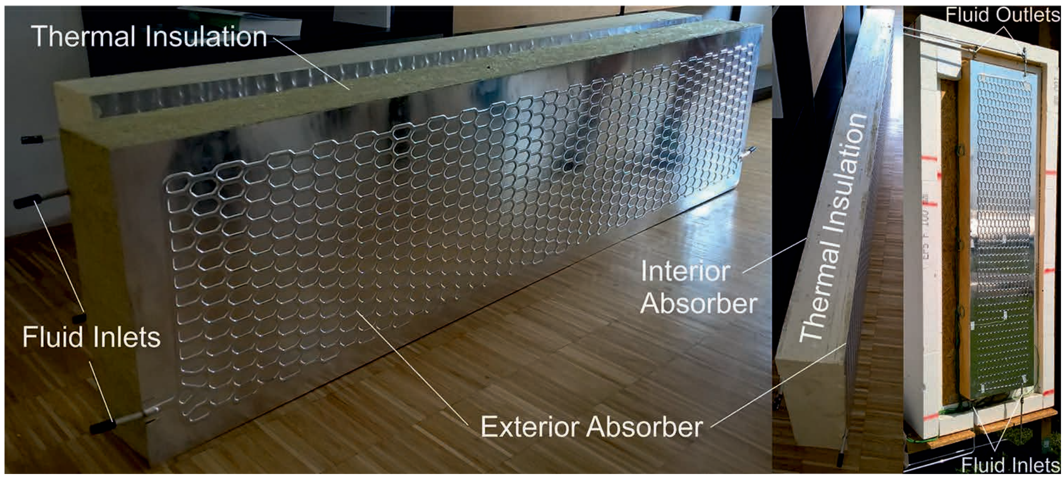


FIG. 1 Photos of a STAF panel equipped with blank aluminium absorbers and a honeycomb pipework

1.3 THERMAL AND STRUCTURAL ANALYSIS METHOD

The first of the two main objectives of this study is the analysis of the thermal behaviour of exterior absorber plates with the CFD (Computational Fluid Dynamics) method in order to optimise the fluid pipe design with regard to solar energy conversion. The second objective is to find an adequate structural analysis method to evaluate different installation situations of a STAF panel, considering the detailed thermal behaviour as boundary condition. In a first approach (Schober & Brandl, 2016) the thermal behaviour was determined with the help of the Software Fluent (ANSYS 18.2 release); the results were extracted at certain points of the exterior and interior absorber plates and used as boundary conditions in a FEM (Finite Element Method) model using the software Abaqus FEA (SIMULIA 6.14 release). Because these results were not accurate enough, another method is used in this study whereby the thermal behaviour and the resulting deformations are simulated with a so-called 'one-way coupled' simulation model (Feenstra, Hofmeyer, Van Herpen, & Mahendran, 2018). Literature shows some interesting findings concerning both numerical methods. For the paper of Ahmed, Leithner, Kosyna, and Wulff (2009), a coupled fluid dynamics and structural analysis for a boiler feed water pump was performed by the authors in order to predict its hydraulic and thermo-mechanical behaviour. In the study of Feenstra et al. (2018), two coupling approaches between CFD and FEM were used to perform CFD fire simulations as well as structural simulations of a room in a building. A one-way coupled CFD-FEM was also used for the analysis of the behaviour of a steel structure under natural fire by Malendowski and Glema (2017). There are a few more studies in which a coupled CFD-FEM simulation method was used (Fritsch et al. 2017; Zhang & Lu 2017; Liang, Luo, & Li, 2018; Kim, Choi, Park, Choi, & Lee, 2012; Peksen, 2015), but none dealt with the thermal and structural behaviour of sandwich panels. For the coupled simulation of this study, the software platform ANSYS Workbench (ANSYS 18.2 release) is used, which includes CAD and meshing software as well as CFD and FEM simulation tools. The flow chart in Fig. 2 shows the setup of the one-way coupled CFD-FEM simulation.

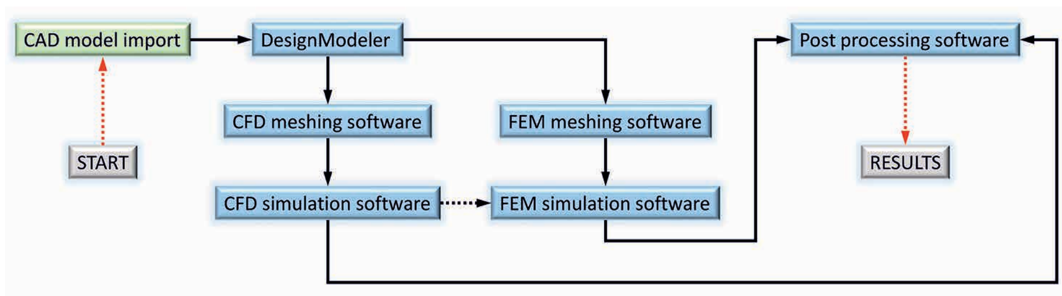


FIG. 2 Flow chart with the simulation setup of the one-way coupled CFD-FEM simulation

Usually, the CFD mesh must be much finer than the FEM mesh in order to consider the complex fluid characteristics, especially for the regions near walls. With the help of the CFD software Fluent, the flow characteristics and temperature distribution of the involved solid and fluid components is calculated. Furthermore, results from the CFD simulation can be used to determine the thermal output and the efficiency of the STAF panel´s exterior absorber. Afterwards, the resulting temperature characteristic of each solid from the CFD simulation serves as thermal boundary condition in the structural simulation (FEM model). With the FEM software from ANSYS, a structural analysis is performed under the influence of thermal deformations as well as deformations that are caused by external wind loads. The results from both simulations are transferred to the ANSYS Post Processing software where all results are evaluated and diagrams, contour plots etc. are created.

2 MEASUREMENTS IN AN OUTDOOR TEST FACILITY

2.1 DESCRIPTION OF THE MEASUREMENT SETUP

Over the course of the research project UNAB, an outdoor test facility was designed and assembled (Hörtenhuber, 2017) in order to use the monitored temperature data for the evaluation of the CFD model (Fig. 3). Furthermore, in the measurements, the comparison between a thermally activated and a non-activated STAF panel (= reference panel) can be observed. The reference panel is representative of a conventional sandwich panel forming the façade of an industrial building; for example, the STAF panel (shown in Fig. 1) consists of two equal absorber plates with the dimensions of 1.75 x 0.5m. The absorber with double-sided inflated fluid pipes has two aluminium plates with a thickness of 0.75mm per plate and the fluid pipes have a hydraulic diameter of 4.5mm. Additionally, the exterior absorber has a solar paint with an absorptivity of 0.95 and an emissivity of 0.85. Fig. 3 shows a photo of the test facility with the two façade elements that were installed in front of two thermally insulated boxes. Furthermore, this figure shows a photo from a thermographic camera, which was taken on 21st of September at 12:15. At this particular time, an actual global (horizontal) radiation of 707 W/m^2 was monitored while the exterior temperature was 16.6 °C. in addition, a very low wind of approximately 0.35 m/s was measured. The exterior absorber of the STAF panel was supplied with water at a volume flow rate of 25.8 l/h and a temperature of 17.8 °C.

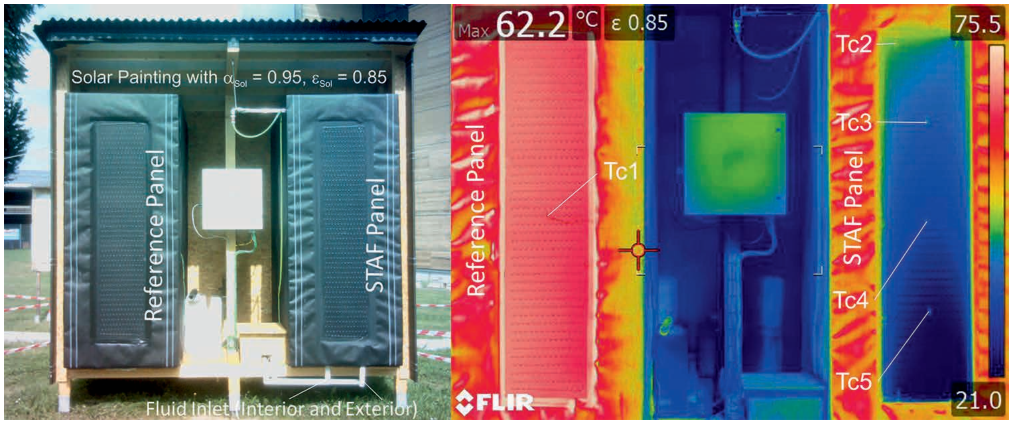


FIG. 3 (Left) Photo of the outdoor test facility. (Right) Thermographic photo during outdoor measurement (from 21st September 2016, 12:15). *(Image by M. Hörtenhuber, 2017).*

The water mass flow rate is monitored with the help of a magnetic-inductive flowmeter which has a measuring uncertainty of 2.5% of the measured value, but which is at least 0.05 l/h. The water temperature is monitored before the exterior absorber inlet as well as after the outlet with Pt100 sensors which have class A accuracy according to DIN EN 60751. The absorbers are equipped with a number of thermocouples (with class 1 accuracy) in order to measure the temperature at the exterior and the absorber plate´s surfaces, as well as inside the thermal insulation.

2.2 MEASUREMENT RESULTS

From 15th September, collected measurement data (shown in Fig. 4) serve as an example to give a short overview about the thermal behaviour of the STAF panel. The climate data are illustrated in the diagram on the left in Fig. 4. This diagram also includes the mass flow rate as well as the water inlet and outlet temperature of the exterior absorber of the STAF panel. The diagram on the right in Fig. 4 shows a comparison between the exterior absorber surface temperature of the reference and the STAF panel. Because the reference panel has an almost uniform temperature distribution, only one thermocouple (Tc1) is installed (illustrated in Fig. 3). The exterior absorber of the STAF panel shows an increasing surface temperature from the bottom to the top, which matches fluid motion that stores heat recovered from the absorption of solar radiation along the path (indicated by the temperature profiles of the thermocouples Tc2-Tc5). The difference between the hottest temperature of the STAF panel and the reference panel was approximately 25K. Furthermore, the maximum difference between water inlet and outlet temperatures occurred between 13:00 and 14:00 with an value of 21.3K, while the average mass flow was approximately 20kg/h over the day. In total, the energy harvesting for the panel on that day was approximately 3.48 kW/(m^2·d). Data were collected from the end of August until the end of November.

2.3 EFFICIENCY OF THE STAF PANEL´S EXTERIOR ABSORBER

With the help of all monitored data, the efficiency of the STAF panel´s exterior absorber is calculated according to the equation of the absorber efficiency (Duffie & Beckman, 1991; Streicher, 2007), which is illustrated in Fig. 5. The red line shows the linear regression of the set points which are calculated with the help of measurement data. The first term of this equation represents the conversion rate of the solar radiation. The second term of the equation considers the effect of convective heat loss of solar thermal collectors, whereas the third term represents the radiative heat loss. On the one hand, for the absorber of the STAF panel, the solar conversion is higher because of the missing glass cover that conventional solar thermal collectors have (shown as blue and green dashed lines in the diagram in Fig. 5).

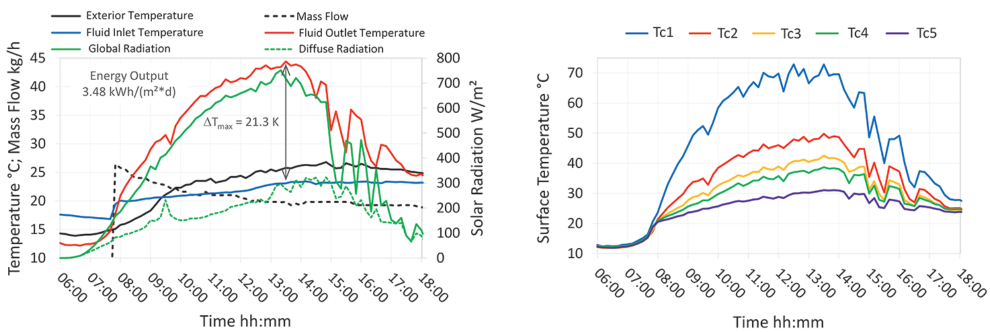


FIG. 4 Excerpt of measurement data from the outdoor test facility from 15th September 2016 between 06:00 and 18:00

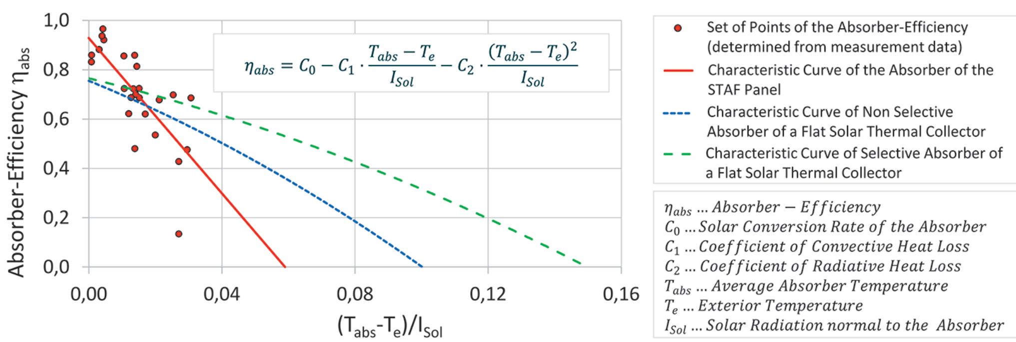


FIG. 5 Comparison of the efficiency between the STAF panel´s exterior absorber and solar thermal collectors

On the other hand, the convective heat loss is much higher when the exterior temperature is lower than the average absorber temperature. Compared to the convective heat loss, the radiative loss is so low that it can be neglected for the STAF panel´s exterior absorber. Generally, the efficiency of the STAF panel´s absorber can be described as good, but it cannot keep up with conventional solar thermal collectors without any improvements. The characteristic absorber efficiency curve can be used in a building and plant simulation in which the yearly energy output can be estimated by use of measured or generated climate data. Due to the scattering of the absorber efficiency's set points the RMSE (Root Mean Square Error) is 0.124, which is quite high. This scattering occurred because the uncovered absorber is strongly influenced by the wind, the conditions of which varied during the outdoor measurements. For this reason, the characteristic curve must be divided into several curves that are created with the help of monitored values for the same wind.

3 THERMAL AND STRUCTURAL ANALYSIS OF THE STAF PANEL WITH COUPLED CFD-FEM SIMULATION METHOD

3.1 DESCRIPTION OF THE CFD MODEL

In order to optimise the absorber geometry, and to improve the fluid pipework, the Computational Fluid Dynamic simulation method was used. With this method, a various number of different absorber geometries (or only sections of an absorber) can be analysed at same exterior boundary conditions. For the proper design of the three-dimensional CFD model and to guarantee a good quality of the simulation results, the monitored data from a tested STAF panel were used. The absorber geometry is designed with the CAD tool, AutoCAD, and is later imported to the ANSYS DesignModeler in form of a Step-File. The CFD mesh and the definition and interconnection of all involved solid and fluid components, as well as the definition of boundary surfaces, are created with the Software ANSYS ICEM. Finally, in the CFD analysis, the simulation is performed in ANSYS Fluent after definition of the physical models and boundary conditions. In Fluent, the simulation is performed under steady state conditions using a 'Pressure-Based' solver. A section of the CFD mesh of the honeycomb absorber from measurement is shown in Fig. 6, together with the resulting water flow characteristic at the outlet region of the absorber's pipework.

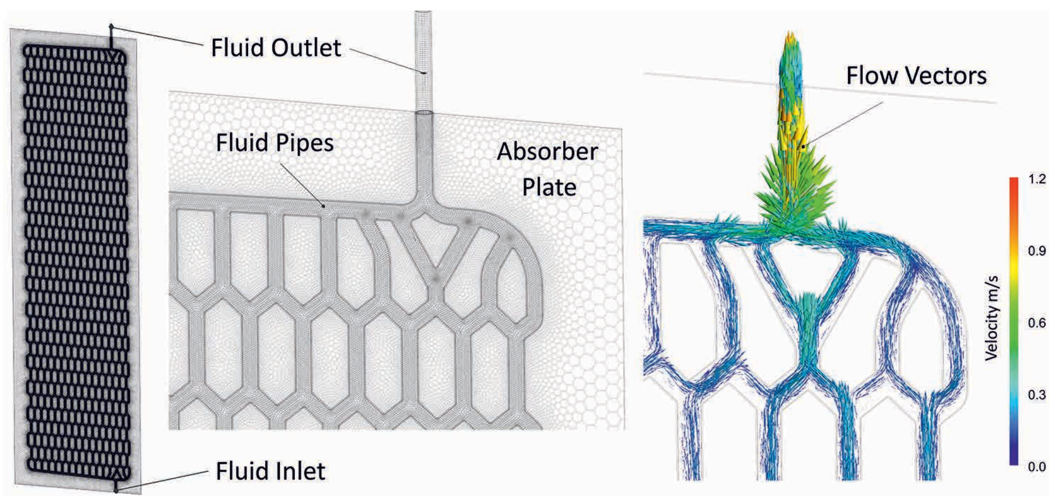


FIG. 6 Picture of the CFD mesh of the honeycomb absorber and a magnified section, with additional visualization of the fluid flow vectors

The final version of the mesh consists of approximately 25 million cells, after the tetrahedron cells are converted into polyhedral cells. This high number of cells is required because of the thin plates and the very flat shape of the fluid pipe. In particular, the fluid domain needs a special design in order to meet the requirements of the used 'Realizable k-e' turbulence model with an enhanced wall treatment. Both literature (Launder & Spalding, 1974) and the ANSYS User Guide state that this model is well suited for fluid dynamic simulations and combined heat transfer effects. Several CFD analyses, regarding thermal behaviour, heat transfer effects, and effects of natural convection, were performed by two of the involved authors (Brandl, Mach, Grobbauer, Hochenauer, 2014; Brandl et al. 2015; Brandl, Mach, & Hochenauer, 2016) in the past. Nevertheless, in this study, different CFD model approaches are also compared and evaluated with the help of the measurement results (see Section 3.2). Furthermore, the fluid inlet is defined as mass flow inlet with the mass flow rate and the fluid inlet temperature as boundary conditions, whereas the fluid outlet is defined as a pressure outlet in the simulation model. At the exterior wall, an outdoor temperature and a solar radiation are defined as boundary conditions, as well as a convective heat transfer coefficient representing the influence of natural convection and wind.

The solar radiation is considered in the form of a radiation temperature (T_{rad} in K) according to the following equation (1) which is derived from Stefan-Boltzmann law. I is the radiation in W/m^2, T_e is the exterior temperature in K, and s is the Stefan-Boltzmann constant (= 5.67e-8 W/(m^{2}K^4)).

$$T_{rad} = \left(T_e^4 + \frac{I}{\sigma} \right)^{0.25}$$

At the inner wall, an interior room temperature and a heat transfer coefficient are defined.
The thermal insulation and the interior plate are considered as virtual layers in the CFD model of the STAF panel with the honeycomb absorber, while real solid and fluid bodies are created in the example of the CFD-FEM coupling (presented in Chapter 3.4). The external heat transfer coefficient a_e in W/(m^{2}K) is calculated according to the following equation (2) from standard VDI 2055. In this equation, L stands for the façade´s height in m and v for the wind speed in m/s.

$$\alpha_e = 3.96 \cdot (v/L)^{0.5}; for (v/L) < 8m^2/s$$
$$\alpha_e = 11/L + 5.8 \cdot [(L \cdot v - 8)/(L \cdot v)] \cdot (v^4/L)^{0.2}; for (v/L) > 8m^2/s$$

3.2 COMPARISON OF THE THERMAL BEHAVIOUR BETWEEN MEASUREMENT AND CFD SIMULATION

Before performing the thermal analysis of the absorber with different fluid pipe designs, the CFD model is evaluated by comparing the temperature data of the STAF panel with the honeycomb absorber, which was installed in an outdoor test facility. In the comparison, the evaluated thermographic photos and the measured water outlet temperature are used. Furthermore, measured values are used as boundary conditions in the CFD model. For this purpose, the data from 21st September are most suitable. At 12:09, a global radiation of 737 W/m^2 perpendicular to the STAF panel was measured with a diffuse fraction of 244 W/m^2. An exterior temperature of 16.6 °C was measured, and the averaged value of the wind speed between 12:00 and 13:00 resulted in a value of 0.35 m/s (= very low wind). The thermocouples inside the box behind the STAF panel measured an average interior temperature of 15.4 °C at that time. The mass flow rate was 25.5 kg/h and the supplied water had a temperature of 17.8 °C. In the CFD model, the water has a density of 998.2 kg/m^3, a specific heat of 4182 J/kgK, and a thermal conductivity of 0.4 W/mK. The absorbers are made of aluminium with a density of 2700 kg/m^3, a specific heat capacity of 896 J/kgK, and a high thermal conductivity of 201 W/mK. Polyurethane is used as thermal insulation between the exterior and interior absorber plate, which has a density of 80 kg/m^3, a specific heat capacity of 1400 J/kgK, and a thermal conductivity of 0.025 W/mK. Because the water supply pipe is partly exposed to the sun, a preliminary CFD simulation, only of this pipe, was performed for the following comparison between measurement and CFD simulations (Fig. 7). The same model parameters are used in the CFD model as in the simulation of the STAF panel. A temperature difference of 0.48K between the measurement sensor and the mass flow inlet of the CFD model of the STAF panel is the result of this preliminary simulation. Therefore, in the CFD model of the STAF panel, a water inlet temperature of 18.3 °C is defined as the boundary condition. In the comparison between the measurement and CFD simulation, a couple of different models were used in order to choose the most suitable model for further analysis. The initial CFD model, which is described in the text above, uses a constant density for the fluid. In the next CFD model the 'Gravity' is activated as well as the option 'Full Buoyancy Effects' in the turbulence model. Furthermore, the density of the fluid is defined as piecewise linear depending on the fluid temperature to enable natural convection inside the pipes of the absorber plate.

A last version of the STAF CFD model is an extension of the model with natural convection. An air-filled domain of 1m is added in front of the exterior absorber which has an inlet and outlet surface (Fig. 7). In this model, the boundary condition of the exterior temperature and the heat transfer coefficient, as well as the external radiation temperature are removed. Instead of the external radiation temperature, the solar calculator from FLUENT is used.

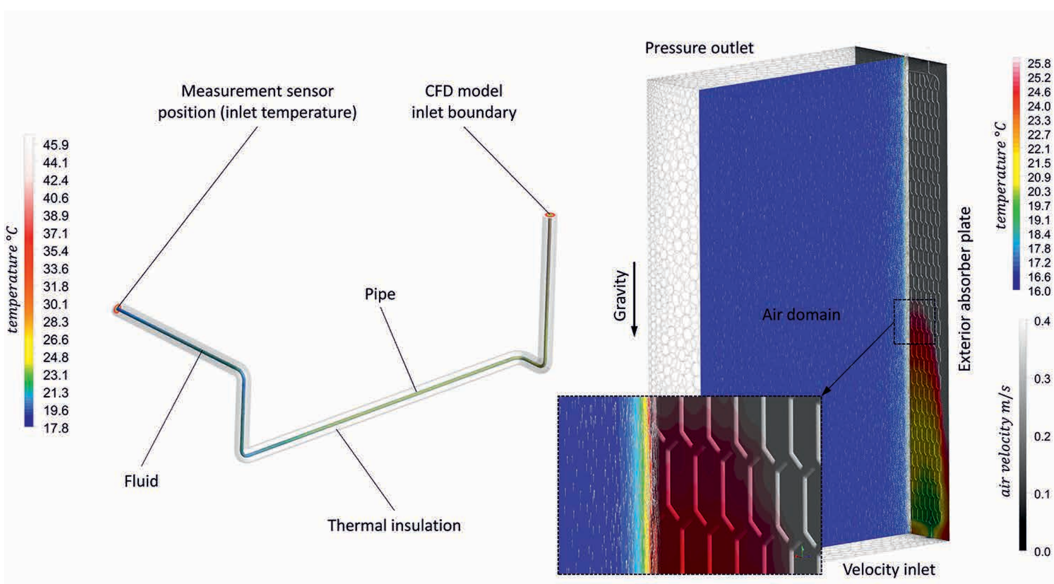


FIG. 7 Temperature contours of the water supply pipe CFD model (left), STAF CFD model with additional air domain (right)

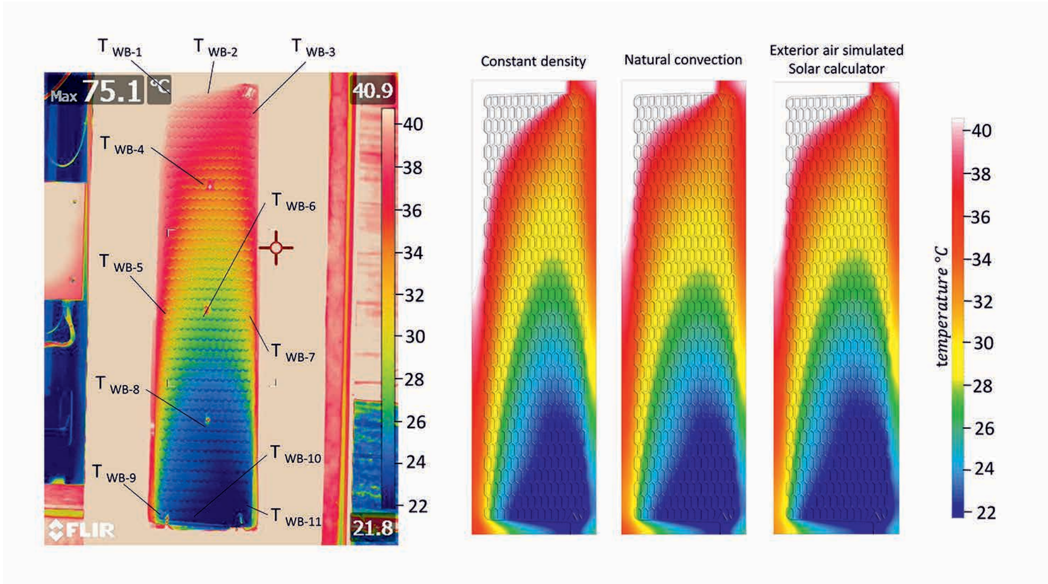


FIG. 8 Comparison between temperature contours from CDF simulations and the thermographic photo (from 21st September 2016, 12:09) of the STAF panel´s exterior absorber

POSITION	Thermo-graphic analysis (TA)	CFD Constant density (CD)	Difference between TA and CD	CFD Natural convection (NC)	Difference between TA and NC	CFD Exterior air and Solar calculator (EASC)	Difference between TA and EASC
	°C	°C	K	°C	K	°C	K
T_{WB-1}	48.1	51.8	3.7	47.7	0.4	46.2	1.9
T_{WB-2}	42.0	44.8	2.8	42.7	0.7	43.4	1.4
T_{WB-3}	36.4	34.5	1.9	34.9	1.5	34.9	1.5
T_{WB-4}	33.2	31.8	1.4	31.7	1.5	31.1	2.1
T_{WB-5}	33.7	36.0	2.3	34.4	0.7	34.1	0.4
T_{WB-6}	29.1	29.5	0.4	29.5	0.4	28.9	0.2
T_{WB-7}	31.5	30.2	1.3	30.4	1.1	29.7	1.8
T_{WB-8}	25.7	24.7	1.0	24.6	1.1	23.9	1.8
T_{WB-9}	27.4	28.6	1.2	27.0	0.4	25.8	1.6
T_{WB-10}	23.1	21.4	1.7	21.4	1.7	20.8	2.3
T_{WB-11}	23.8	20.9	2.9	20.9	2.9	20.9	2.9

TABLE 1 Comparison of surface temperatures of the exterior absorber plate between thermographic analysis (from 21st September 2016, 12:09) and the CFD simulation results

Fig. 8 shows the comparison between a thermographic photo and the resulting temperature contours of the exterior absorber from CFD simulations. Additionally, those positions are indicated where the temperature of the thermographic photo is evaluated (with the help of the software 'ResearchIR') and compared to the simulation results. A summary of this comparison can be found in Table 1. Generally, all temperature characteristics look similar. Considering the comparison of the water outlet temperature that is measured and simulated, data match very well. The difference between the investigated measured and simulated values at exterior temperatures of the absorber plate is a deviation between 3.7 and 2.9K. Because the CFD model with natural convection shows a better agreement with the thermographic photo and the evaluated temperatures, this model is proposed for further analyses with varying fluid pipe designs. A comparison between simulated and measured water outlet temperatures and the resulting thermal output from other days is also performed. The results are summarised in Table 2 and show a good agreement between measurement and simulation.

DATE	TIME	EXTERIOR TEMP.	SOLAR RADIA-TION	MASS FLOW RATE	FLUID INLET TEMP.	DT-PIPE-SUPPLY (SIM.)	FLUID OUTLET TEMP. (MEAS.)	FLUID OUTLET TEMP. (SIM.)	THERMAL OUTPUT (MEAS.)	THERMAL OUTPUT (SIM.)
dd.mm.yyyy	hh:mm	°C	W/m²	kg/s	°C	°C	°C	°C	W/m²	W/m²
01.09.2016	12:00	25.6	630	0.0124	25.7	0.22	28.8	28.4	185	162
02.09.2016	12:00	27.1	652	0.0075	24.7	0.38	30.2	29.5	197	174
20.09.2016	14:02	17.5	621	0.0031	20.1	0.55	48.9	49.1	432	435
21.09.2016	12:09	16.6	737	0.0071	17.8	0.48	36.9	36.3	644	627
23.09.2016	13:00	20.4	749	0.0063	18.2	0.41	38.6	38.5	617	614

TABLE 2 Comparison of water outlet temperature and the thermal output between measurement and CFD simulation at different times

3.3 RESULTS FROM THERMAL ANALYSIS (CFD)

After the positive evaluation of the numerical method and the CFD model, this study shows the analysis of the thermal behaviour and thermal output of three further pipe designs for the absorber plate, with the dimensions 1.75 x 0.5m. For this analysis, the following boundary conditions are used: a solar radiation of 1000 W/m² at an angle of 45 °; an exterior temperature of 30 °C and a heat transfer coefficient of 25 W/m²K; an interior temperature of 20 °C and a heat transfer coefficient of 5 W/m²K; a fluid inlet temperature of 15 °C and a mass flow rate of 50 kg/h; and a solar absorptivity of 0.95 for the exterior absorber surface. The comparison includes four different layouts: (a) the honeycomb absorber which is also used in the comparison with the in-situ measurements, (b) a harp absorber with 14 vertical, parallel fluid pipes, (c) again a harp absorber but with only 10 fluid pipes, and (d) another harp absorber but with 11 vertical, parallel arranged fluid pipes and more complex inlet and outlet pipework. The computed temperature contours of these four absorbers are illustrated in Fig. 9. All absorbers have (f) one-sided inflated fluid pipes, except the honeycomb absorber which has (e) double-sided inflated pipes. The relevant results from CFD simulations are summarised in Table 3.

The highest water outlet temperature of 27.9 °C is achieved with the absorber with 14 vertical fluid pipes (b) followed by the honeycomb absorber for which the fluid outlet temperature is 27.8 °C, and the absorber with 10 pipes which has a water outlet temperature of 27.7 °C. The lowest fluid outlet temperature (27.4 °C) occurs for the absorber (d) with the more complex inlet and outlet geometry. The resulting thermal output is 857 W/m² for the absorber (b), 851 W/m² for absorber (a), 846 W/m² for absorber (c), and 822 W/m² for absorber (d). The honeycomb absorber (a) with the double-sided inflated fluid pipe shows the lowest pressure difference of 1056 Pa between water inlet and outlet. The absorber (b) with the 14 pipes shows a pressure difference of 1424 Pa and 1599 Pa for the absorber (c) with 10 pipes. Again, the absorber (d) shows the worst case with a pressure difference of 2936 Pa.

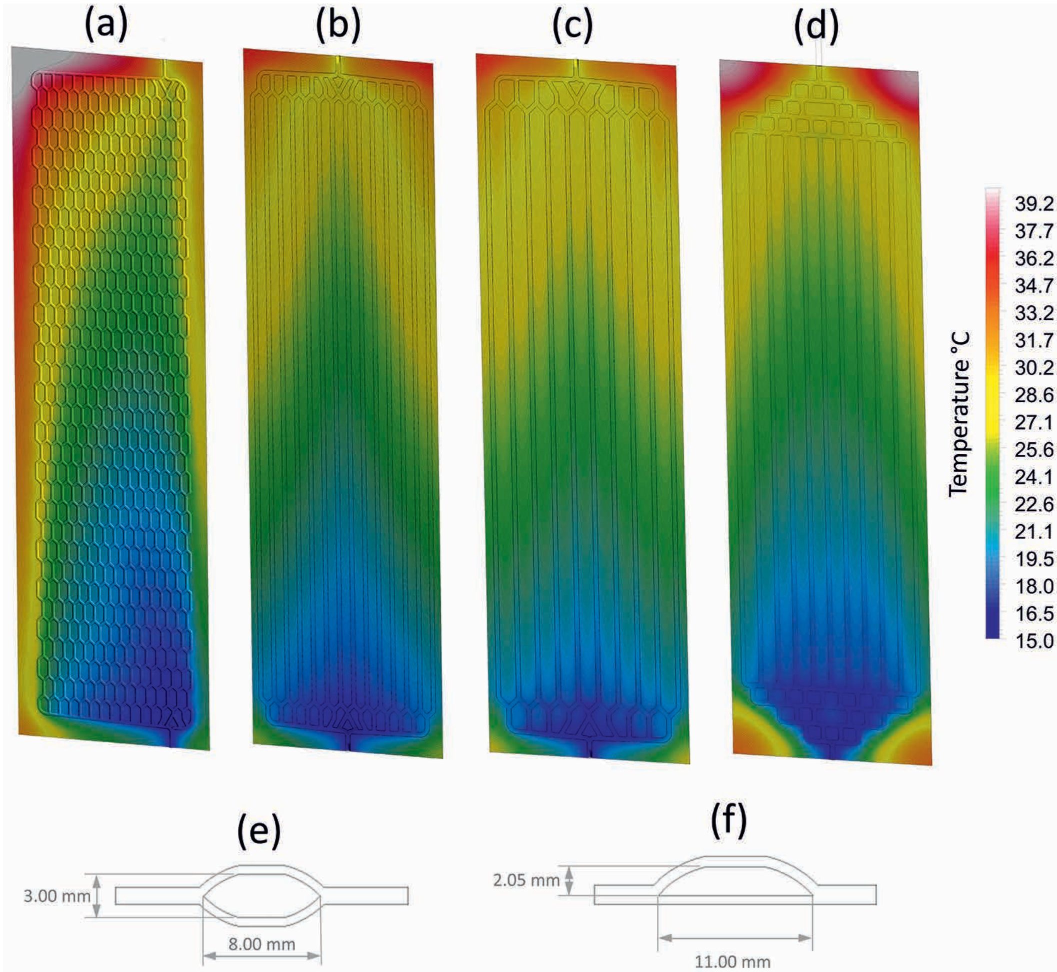


FIG. 9 Illustration of the absorber temperature contours of an absorber with a (a) honeycomb, (b) 14 vertical pipe harp, (c) 10 vertical pipe harp, and (d) 11 vertical pipe harp absorber. Schematic (e) shows the cross section of the double-sided inflated pipe profile, and (f) of the one-sided inflated pipe profile.

PIPE DESIGN	FLUID OUTLET TEMPERATURE	THERMAL OUTPUT	PRESSURE DIFFERENCE
	°C	W/m²	Pa
Honeycomb	27.8	851	1056
Harp, 14 vertical pipes	27.9	857	1424
Harp, 10 vertical pipes	27.7	846	1599
Harp, 11 vertical pipes	27.4	822	2936

TABLE 3 Comparison of the water outlet temperature, the thermal output, and the pressure difference between the absorber designs

3.4 DESCRIPTION AND RESULTS FROM STRUCTURAL ANALYSIS (FEM)

The thermal analysis is followed by a structural analysis in which the deformation of the STAF panel is simulated with the help of the Finite Element Method (FEM). The same CFD model is used as a basis for the model, but the mesh is much coarser. Furthermore, the fluid domain is not necessary in the FEM simulation and can be neglected in the model. In the structural analysis, the thermal deformations are considered, as well as the pressure caused by wind loads. Two different wind characteristics are observed: low wind and strong wind. While, for low wind the pressure is very small, a dynamic pressure p_d of 1000 Pa is set as an additional boundary condition in the FEM model with strong wind. The dynamic pressure of 1000 Pa represents a wind speed of approximately 150 km/h according to equation (3), which is more than the maximum occurring wind in the region of Austria. The external heat transfer coefficient is increasing to a value of 100 W/m^2K according to equation (2). In the equation r is the density of the fluid in kg/m^3 and v is the wind speed in m/s.

$$p_d = \frac{1}{2} \cdot \rho \cdot v^2$$

For the determination of the thermal deformations, the results from the thermal analysis (CFD) are used as boundary conditions. For this reason, the temperature characteristic of each solid body is imported in the FEM model. This study presents the comparison of the deformation between a 3.5 x 1.0 x 0.15m STAF panel and a conventional aluminium sandwich panel with polyurethane foam as the thermal insulator, and which has the same dimensions as the STAF panel. One-sided inflated fluid pipes are used, and the absorber plates show a thickness of 1.5mm. The STAF panel contains 20 vertical fluid pipes which have individual inlets and outlets. The water is evenly supplied to the pipes (exterior and interior sides) at the bottom of the STAF panel with a mass flow rate of 100 kg/h and the water inlet temperature is measured at 10°C. At the exterior side, the water is heated due to 1000 W/m^2 solar radiation and a solar angle of 45°, while the exterior temperature is 30°C. At the interior side of the panel, a room temperature of 25°C is defined. The heat transfer coefficients and absorptivity have the same values as in the simulation in Chapter 3.3. Fig. 10 shows the resulting temperature profiles from CFD simulation (a-d) as well as the deformations from FEM simulation (e-h) of the conventional sandwich and the STAF panel. The maximum deformations occurred at the middle of the panel for the conventional sandwich panel and slightly above the middle for the STAF panel. Under low wind conditions, the maximum deformation is approximately 6.5mm for the conventional panel and about 3.6mm for this version of the STAF panel. Under strong wind, the maximum deformation is generally higher, with values of 17.5mm for the conventional sandwich panel and 15.6mm for the STAF panel. The results from CFD and FEM simulations are summarised in Table 4.

	AVERAGED SURFACE TEMPERATURE FOR LOW WIND	AVERAGED SURFACE TEMPERATURE FOR STRONG WIND	MAXIMUM DEFORMATION FOR LOW WIND	MAXIMUM DEFORMATION FOR STRONG WIND
	°C	°C	mm	mm
Exterior plate STAF panel	25.3	28.6	3.6	15.6
Interior plate STAF panel	12.2	12.2	3.6	15.6
Exterior plate sandwich panel	51.1	36.3	6.5	17.5
Interior plate sandwich panel	25.8	25.4	6.5	17.5

TABLE 4 Summary of the averaged surface temperature of the exterior and the interior absorber and the simulated maximum deformations

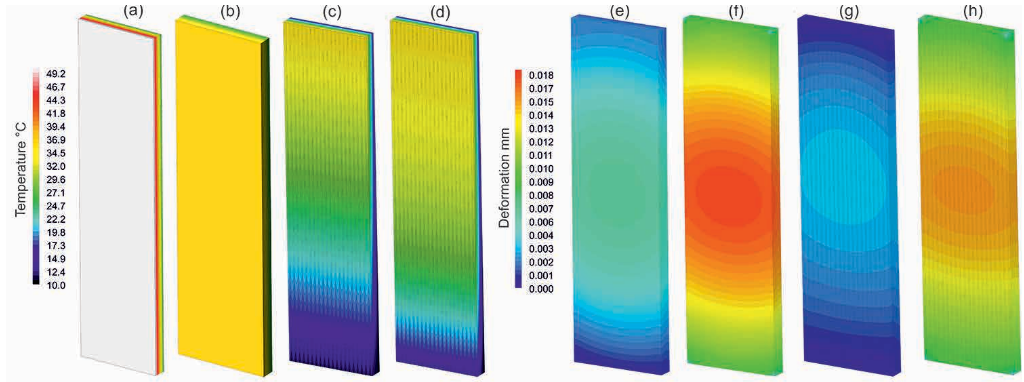


FIG. 10 Temperature contours of (a) the sandwich panel for low wind, (b) sandwich panel for strong wind, (c) STAF panel for low wind, (d) STAF panel for strong wind. Deformation of the (e) sandwich panel for low wind, (f) sandwich panel for strong wind, (g) STAF panel for low wind, (h) STAF panel for strong wind.

4 CONCLUSION AND OUTLOOK

In order to fulfil one of the main objectives of this study (mentioned in Section 1.3), the 'one-way coupling' between the two numerical simulation methods CFD-FEM has been implemented and allows the determination of the deformations caused by heat and cooling effects and/or wind loads.

Furthermore, the CFD model was evaluated with the help of measurement data from an outdoor test facility and thermographic photos of the STAF panel´s exterior absorber. A good agreement was achieved between the measured and simulated water outlet temperature of an absorber with a honeycomb pipework. Furthermore, from the comparison of the temperature noted between the CFD simulation and the thermographic images, it was concluded that the CFD model is accurate enough for further analyses.

In order to optimise the pipe design of the STAF panel with a honeycomb absorber from the outdoor test facility (and fulfil the remaining main objective of this study), three further absorber geometries were designed and analysed with the help of CFD simulations. The absorber with the 14 vertical, parallel arranged fluid pipes with one side inflation shows the best thermal performance. The lowest pressure difference was achieved for the honeycomb absorber with double-sided inflated fluid pipes.

From the results of the FEM simulation, it was concluded that the static behaviour was slightly improved due to the integrated fluid pipes. Generally, the mechanical stresses and thermal deformations are within the acceptable tolerances.

Based on the completed and pending thermal and static analyses, prototypes will be produced and measured under real climate conditions. The measurement data can be used for a final optimisation of the STAF panel. Therefore, a new outdoor test facility will be installed, which will allow the parallel analysis of five STAF panels.

Acknowledgements
All contents of this publication are part of the already completed project 'Umsetzung nachhaltigen Bauens durch optimierte Projektsteuerungsprozesse und integrale Gebäudehüllen' (UNAB), which was funded by the 'Zukunftsfonds Steiermark' des Landes Steiermark, as well as of the ongoing Interreg-project 'ABS-Network SIAT 125' at Graz University of Technology, Austria. Interreg V-A Slovenia-Austria is a cross-border cooperation programme between Slovenia and Austria in the programme period 2014-2020. An overview of the project and a list of all participants can be found at the following link: http://abs-network.eu/en

References
Ahmed, S., Leithner, R., Kosyna, G., & Wulff, D. (2009). Increasing reliability using FEM–CFD. *World Pumps, 509*, pp.35-39.

BKI Baukosteninformationszentrum [Construction Costs Information Center] (2018). BKI Baukosten Neubau 2018 - Teil 1-3 [Construction costs of new buildings 2018 - part 1-3] : Statistische Kostenkennwerte Gebäude, Positionen und Bauelemente [Statistical cost factors of buildings, positions and parts]. Stuttgart: BKI 2018.

Brandl, D., Mach, T., Grobbauer, M., Hochenauer, C. (2014). Analysis of ventilation effects and the thermal behaviour of multifunctional façade elements with 3D CFD models. *Energy and Buildings, 85*, pp.305-320.

Brandl, D., Mach, T., Kaltenecker, P., Sterrer, R., Neururer, C., Treberspurg, M., & Hochenauer, C. (2015). CFD assessment of a solar honeycomb (SHC) façade element with integrated PV cells. *Solar Energy, 118*, pp.155-174.

Brandl, D., Mach, T., & Hochenauer, C. (2016). Analysis of the transient thermal behaviour of a solar honeycomb (SHC) façade element with and without integrated PV cells. *Solar Energy, 123*, pp.1-16.

Brötje, S., Kirchner, M., & Giovannetti, F. (2018). Performance and heat transfer analysis of uncovered photovoltaic-thermal collectors with detachable compound. *Solar Energy, 170*, pp.406-418.

Brucha Ges.m.b.H. (1948). Retrieved from http://www.brucha.com/

Del Col, D., Padovan, A., Bortolato, M., Dai Prè, M., & Zambolin, E. (2013). Thermal performance of flat plate solar collectors with sheet-and-tube and roll-bond absorbers. *Energy, 58*, pp.258-269.

Duffie, J. & Beckman, W. (1991). *Solar engineering of thermal processes.* New York: Wiley-Interscience Publication, John Wiley & Sons, Inc.

Ebrahimi, H., Someh, L. K., Norato, J., & Vaziri, A. (2018). Blast-resilience of honeycomb sandwich panels. *International Journal of Mechanical Sciences, 144*, pp.1-9.

Eizadjou, M., Manesh, H. D., & Janghorban, K. (2009). Mechanism of warm and cold roll bonding of aluminum alloy strips. *Materials & Design, 30,* 10, pp.4156-4161.

EN 14509 (2013). *Self-supporting double skin metal faced insulating panels – Factory made products – Specifications*.

Feenstra, J.A., Hofmeyer, H., Van Herpen, R.A.P., & Mahendran, M. (2018). Automated two-way coupling of CFD fire simulations to thermomechanical FE analyses at the overall structural level, *Fire Safety Journal, 96*, pp.165-175.

Fritsch, A., Uhlig, R., Marocco, L., Frantz, C., Flesch, R., & Hoffschmidt, B. (2017). A comparison between transient CFD and FEM simulations of solar central receiver tubes using molten salt and liquid metals, *Solar Energy, 155*, 2017, pp.259-266.

Haseli, M., Layeghi, M., & Hosseinabadi, H. Z. (2018). Characterization of blockboard and battenboard sandwich panels from date palm waste trunks. *Measurement, 124*, pp.329-337.

Hashemi, S. J., Razzaghi, J., Moghadam, A. S., & Lourenço, P. B. (2018). Cyclic testing of steel frames infilled with concrete sandwich panels. *Archives of Civil and Mechanical Engineering, 18*, 2, pp.557-572.

Hermes, C.J.L., Melo, C., & Negrão, C.O.R. (2008). A numerical simulation model for plate-type, roll-bond evaporators. *International Journal of Refrigeration, 31*, 2, pp.335-347.

Hörtenhuber, M. (2017). *Konstruktion, Aufbau und Inbetriebnahme eines Versuchsstandes zur Ermittlung des thermischen Verhaltens eines integralen Fassadenelementes* [Construction, assembly and commissioning of an experimental test stand for the analysis of the thermal behaviour of an integral façade element]. Graz: Technische Universität Graz

IC Market Tracking (2016). *Sandwichpaneele in Europa* [Sandwich panels in europe]. Retrieved from https://www.interconnection-consulting.com/de/industry/119

Kim, S., Choi, J., Park, J., Choi, Y., & Lee, J. (2013). A coupled CFD-FEM analysis on the safety injection subjected to thermal stratification. *Nuclear Engineering and Technology, 45, 2*, pp.237-248.

Koschade, R. (2011). *Sandwichbauweise: Konstruktion, Systembauteile, Ökologie (Detail Spezial) [Sandwich construction: construction, system components, ecology (detail special)]*, Inst. f. Int. Architektur Dokumentation [Institute of int. architecture documentation].

Launder, B.E. & Spalding, D.B. (1974). The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics and Engineering, 3, 2*, pp.269-289.

Li, Z. Zheng, Z., Yu, J., & Lu, F. (2017). Deformation and perforation of sandwich panels with aluminum-foam core at elevated temperatures, *International Journal of Impact Engineering, 109*, pp.366-377.

Liang, R., Luo, Y., & Li, Z. (2018). The effect of humping on residual stress and distortion in high-speed laser welding using coupled CFD-FEM model, *Optics & Laser Technology*, 104, pp.201-205.

Malendowski, M., & Glema, A. (2017). Development and Implementation of Coupling Method for CFD-FEM Analyses of Steel Structures in Natural Fire, *Procedia Engineering, 172*, pp.692-700.

Missoum, S., Lacaze, S, Amabili, M., & Alijani, F., (2017). Identification of material properties of composite sandwich panels under geometric uncertainty. *Composite Structures, 179*, pp.695-704.

Peksen, M. (2015). 3D CFD/FEM analysis of thermomechanical long-term behaviour in SOFCs: Furnace operation with different fuel gases. *International Journal of Hydrogen Energy, 40*, 36, pp.12362-12369.

Quintana, J. M., & Mower, T. M. (2017). Thermomechanical behavior of sandwich panels with graphitic-foam cores. *Materials & Design, 135*, pp.411-422.

Ravi, P. S., Krishnaiah, A., Akella,S., & Azizuddin, M. (2015). Evaluation of Inside Heat Transfer Coefficient of Roll Bond Evaporator for Room Air Conditioner. *International Journal of Innovative Research in Science, Engineering and Technology, 4, 5*, pp.3378-3384.

Righetti, G., Zilio, C., & Longo, G. A. (2014). Experimental Analysis of R134a and R1234ze (E)Flow Boiling Inside a Roll Bond Evaporator, *International Refrigeration and Air Conditioning Conference, Paper 1404.*

Schober, H. & Brandl, D. (2016). Integrale Gebäudehüllen - Entwicklung eines solarthermisch aktivierten, multifunktionalen Fassadenpaneels [Integral building envelopes - Development of a solar thermally activated, multifunctional façade panel], *Gleisdorf SOLAR 2016 - Internationale Konferenz für solares Heizen und Kühlen, Gleisdorf, Österreich.*

Streicher, W. (2007). Sonnenergienutzung (Vorlesungsskriptum) [Use of solar energy (lecture script)], Institut für Wärmetechnik: Technische Universität Graz.

Sun, X., Wu, J., Dai, Y., & Wang, R. (2014). Experimental study on roll-bond collector/evaporator with optimized-channel used in direct expansion solar assisted heat pump water heating system, *Applied Thermal Engineering, 66*, 1–2, pp.571-579.

Talum d.d. (1942). Retrieved from http://www.talum.si/.

Yazdani Sarvestani, H. , Akbarzadeh, A.H., Niknam, H., & Hermenean, K. (2018). 3D printed architected polymeric sandwich panels: Energy absorption and structural performance, *Composite Structures, 200*, pp.886-909.

Yuan, W., Wang, J., Song, H., Ma, T., Wu, W., Li, J., & Huang, C. (2018). High-power laser resistance of filled sandwich panel with truss core: An experimental study. *Composite Structures, 193*, pp.53-62.

Zhang, Y., & Lu, T. (2017). Unsteady-state thermal stress and thermal deformation analysis for a pressurizer surge line subjected to thermal stratification based on a coupled CFD-FEM method. *Annals of Nuclear Energy, 108*, pp.253-267.

Modelling Envelope Components Integrating Phase Change Materials (PCMs) with Whole-Building Energy Simulation Tools: A State of the Art

Albert Castell[1*], Marc Medrano[2], Francesco Goia[3]

* Corresponding author
1 Department of Computer Science and Industrial Engineering, University of Lleida, Lleida, Spain, acastell@diei.udl.cat
2 Department of Computer Science and Industrial Engineering, University of Lleida, Lleida, Spain
3 Department of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology, Trondheim, Norway

Abstract

Building envelope systems that integrate Phase Change Materials (PCMs) are solutions aimed at increasing the thermal energy storage potential of the building envelope while keeping its mass reasonably low. Building envelope components with PCMs can be either opaque or transparent and can be based on different types of PCMs and integration methods. In opposition to conventional building components, these elements present thermal and optical properties that are highly non-linear and depend to a great extent on the boundary conditions. Such a characteristic requires the system development and optimisation process during the design phase to be carried out with particular care in order to achieve the desired performance. In this paper, a review of the existing modelling capabilities of different building energy simulation (BES) tools for PCM-based envelope components is reported, and the main challenges associated with the modelling and simulation of these systems through the most popular BES tools (among them, EnergyPlus, IDA-ICE, TRNSYS, IES-VE, and ESP-r) are highlighted. The aim of this paper is to summarise the evidence found in the literature of the latest development in the successful use of BES to replicate the thermal and optical behaviour of opaque and transparent components integrating PCMs, in order to provide the community of professionals with an overview of the tools available and their limitations.

Keywords

Phase Change Materials, building envelope, modelling, simulation

DOI 10.7480/jfde.2018.3.2572

1 INTRODUCTION

A Phase Change Material (PCM) is a material that presents a change of its phase of aggregation within a desired temperature range and it is used to store and release thermal energy. Latent heat presents higher energy densities compared to sensible heat, thus reducing the amount of required material and volume to store the same amount of energy. The PCM absorbs energy by changing its phase from solid to liquid, and releases that energy by changing its phase from liquid to solid. The use of PCM in building facades aims at reducing the indoor temperature fluctuations, delaying the air temperature peaks, and blocking the incoming radiation when used in transparent components. As a result, thermal comfort is increased, and/or energy consumption is reduced.

1.1 PCM IN OPAQUE COMPONENTS

Different materials and systems can be used to increase the thermal inertia in opaque building envelopes. When related to PCM, the main parameters to consider are as follows: material and thermphysical properties (Cabeza, Castell, Barreneche, de Gracia, & Fernández, 2011); charging/discharging method (Navarro et al. 2016a and b); and integration system (Navarro et al. 2016b).

1.2 PCM IN TRANSPARENT COMPONENTS

An important feature of several PCMs (among them, paraffin wax, salt hydrates) is that they are (partially) transparent to solar radiation. This property makes them suitable for integration not only in opaque components, but also in transparent components (Silva, Vicente, & Rodrigues, 2016; Vigna, Bianco, Goia, & Serra, 2018). When coupled with transparent or semi-transparent components, the PCM becomes an integrated layer with the function of both thermal energy storage and solar shading (Goia, Perino, & Serra, 2014).

1.3 PECULIAR THERMOPHYSICAL AND OPTICAL PHENOMENA OF PCMS

Subcooling

Subcooling (also called supercooling) happens when the PCM solidifies at a lower temperature than the solidification temperature (Bony & Citherlet, 2007). This phenomenon modifies the temperature range where the PCM will store/release the latent energy, and can significantly affect the behaviour and functionality of the PCM. In most simulations of PCM, the effect of subcooling is neglected. This is an acceptable assumption for low rates of subcooling, but it is problematic when subcooling reaches the order of magnitude of the driving temperature gradient between the heat transfer fluid and the storage (Günther, Mehling, & Hiebler, 2007).

Hysteresis

Hysteresis happens when the solidification temperature is different from the melting temperature. Subcooling is then a common cause of hysteresis (Bony & Citherlet, 2007; Mehling & Cabeza, 2008). Hysteresis is also commonly neglected in modelling PCM-based components in software tools for

Building Energy Simulation (BES). Both subcooling and hysteresis are considered to be two main sources of inaccuracy in modelling PCM-based components (Kośny, 2015).

Convective heat exchange

Heat transfer by convection with PCM is different from ordinary convection. PCM can transport significant amounts of latent heat in the melting temperature range with comparatively little fluid movement and the density changes that drive convection are much stronger. In most simulations, the effect of natural convection is neglected, and is often included (both experimentally and numerically) (Fantucci, Goia, Perino, & Serra. 2018) in the conductive heat transport – i.e. an equivalent conductivity, which also accounts for the contribution of convection in liquid phase, can be used.

PCM optical properties

When a PCM is integrated in a transparent system, its optical properties become driving elements in the thermophysical behaviour of the system. The optical properties of PCM layers are highly dependent on the state of aggregation of the PCM: in solid/musky state, the PCM layer behaves like a highly diffusive material characterised by high scattering phenomena; in a fully liquid state, the behaviour shifts to that of a conventional transparent component, with dominating direct-to-direct transmission mode (Goia, Zinzi, Carnielo, & Serra, 2015). This dynamic feature leads to more complex information to be experimentally collected in order to describe the performance of these glazing systems.

1.4 AIM OF THE PAPER

The aim of this paper is to compare the available BES models capable of simulating PCM in building envelopes, as well as to summarise the evidence found in the literature of the latest development in the successful use of BES to replicate the thermal and optical behaviour of opaque and transparent components integrating PCMs. The paper targets, in particular, the design professionals' community, as well as graduate students and researchers who are currently approaching the modelling and simulation of PCM-based solutions with a limited background in the field.

It is not an intention of this paper to deepen the reasons for adopting PCMs in building, nor to report evidence of the effect of such implementations. Readers interested in these topics can easily find innumerable literature review papers addressing these questions. On the contrary, this paper focuses on the overview of the BES tools available for modelling and simulating PCM-based envelopes, along with their potentials and limitations.

2 SIMULATION REQUIREMENTS

Phase Change Materials integrated in building components affect its thermal performance. Thus, accurate modelling of PCM must be linked and performed in conjunction with the thermal simulation of buildings.

The dynamics of melting and solidification involve a moving boundary that separates the two different phases with drastically different transport properties. Moreover, the PCM behaviour is highly non-linear when changing phase, since its enthalpy (energy storage capacity) changes dramatically with temperature. Therefore, numerical methods are required, and simplified techniques such as conduction transfer functions (CTF) are unsuitable (Cabeza, 2015).

Some numerical models attempt to approximate the solution to simplified Stefan problems. These so-called 'strong formulations' determine the moving solid-liquid boundary and the temperature profiles, and can be based on either fixed or variable grid methods (Hu & Argyropoulos, 1996). However, these models require too much computational effort for practical applications. Therefore, the so-called "weak formulations" are commonly used to simulate the behaviour of a PCM system and to represent the absorption and release of energy. Some of these formulations are the effective heat capacity method, heat integration method, source-based method, and the enthalpy method. Nowadays, the effective heat capacity method and the enthalpy method are the most extended ones (Voller, 1997).

These methods (both weak and strong formulation) can be, and have been, applied to both PCM in opaque and in transparent/translucent building envelope systems. Though it is reasonable to expect that the performance of these methods is independent from the application in an opaque or in a transparent/translucent system, it must be observed that dedicated investigations that compare them in the setting of a transparent/translucent building system have not yet been carried out. All the above-mentioned approaches have also been adopted for modelling PCM layers in the transparent building envelope.

PCM simulation requires short time steps and fine discretisation of the physical domain in order to avoid numerical errors and/or phase-change jumping. Moreover, special attention must be paid in the determination of the temperature-enthalpy curve. Other physical phenomena can also be included in the models, such as convection heat transfer inside the PCM, subcooling of the PCM, and enthalpy hysteresis.

When integrated in transparent or semi-transparent components exposed to solar radiation, non-linearity is also seen in the optical properties of the PCM layer, which becomes an important variable in the simulation as they determine the interaction with the solar radiation – and ultimately most of solar energy intercepted by the layer. In general, the optical behaviour of these systems can be modelled with different degrees of accuracy, ranging from the solution of the full radiative heat transfer equation (Ishimaru, 1978) with the 3-flux approximation (Weinläder, Beck, & Fricke, 2005) by use of a scaling concept (McKellar & Box, 1981), to modelling strategies that reduce the computational effort in the simulation by always treating the PCM layer as a non-diffuse medium (Goia, Perino, & Haase, 2012; Gowreesunker Stankovic, Tassou, & Kyriacou, 2013; Li et al. 2016, Liu et at. 2016) – but incorporating the complexity of the optical behaviour in the solar coefficient used in the models. In any case, these optical properties must be temperature dependent.

Modelling based on raytracing techniques through the bulk material (and in the adjacent room) are mandatory when detailed daylighting analyses (both in terms of natural light distribution and of visual comfort) are to be carried out. In these cases (Giovannini, Goia, Lo Verso, & Serra, 2017), the full set of optical properties for the solar range (i.e. the absorption coefficient and the scattering coefficient, which together give the extinction coefficient and the phase function, giving the probability that radiation with a certain propagation direction is scattered into a certain solid angle around the direction) is necessary. Alternatively, the use of experimentally characterised (Andersen, Roecker, & Scartezzini, 2005) Bidirectional (Optical) Distribution Functions (in the visible range) can represent a suitable alternative that reduces the simulation complexity by avoiding the modelling of the light ray paths within the bulk of the material.

Further assumptions on the optical properties of the PCM layer, supported by spectrophotometric analysis (Goia et al., 2015), may lead to the consideration of a PCM layer with a thickness greater than a few millimetres as a perfectly diffusive material, when in solid state, and as a fully homogeneous and non-scattering material, when in liquid state. In such an approach, the modelling of the PCM layer can be carried out by considering it as a Lambertian surface (in solid and musky state) and a conventional non-scattering material when in liquid state (Giovannini et al., 2017).

Finally, control strategies can be crucial for the correct operation of PCM systems. For passive systems, no control strategy is directly applied, since the phase change process is controlled by the boundary conditions – and, therefore, possible control strategies must rely on the control of, for example, ventilation rate, or indoor air temperature. On the other hand, for active and hybrid systems, different control strategies can be applied, and their influence in the PCM behaviour is very important (de Gracia et al., 2013; de Gracia, Navarro, Castell, & Cabeza, 2015a; de Gracia, Fernández, Castell, Mateu, & Cabeza, 2015b).

The need to adopt suitable control strategies is particular evident when PCMs are integrated in transparent/translucent building envelope systems, since in these configurations the systems can easily receive more (solar) energy than the latent heat available. The control over the incoming radiation – either through shading systems (Manz, Egolf, Suter, & Goetzberger, 1997), prismatic glass panes (Grynning, Goia, Rognvik, & Time, 2013), or other dynamic layers such as, for example, thermotropic layers (Bianco, Cascone, Goia, Perino, & Serra, 2017a; Bianco, Cascone, Goia, Perino, & Serra, 2017b) – as well as of the discharge of the collected latent heat – for example, through a transparent ventilated cavity in which the PCM layer is installed (Elarga, Goia, Zarrella, Dal Monte, & Benini, 2016) is of great importance.

3 IMPLEMENTATION OF PCMS MODELLING IN BUILDING ENERGY SIMULATION TOOLS

There are many numerical models available, capable of simulating the inclusion of PCM in building envelopes. Those most widely used are in TRNSYS (cf. section 3.1) and EnergyPlus (cf. section 3.2), because they have, for a long time, been integrating direct methods for simulating PCM layers (at least in opaque components).

However, there are also other software tools that have had for a long time (ESP-r, cf. section 3.3), or have just recently added (IDA-ICE, cf. section 3.5), dedicated sub-routines that allow the simulation of PCM layers (again, in opaque components only) to be carried out in a rather straightforward way.

The use of different simulation approaches, not based on dedicated sub-routines, has also been applied in other tools (e.g. IES-VE, cf. section 3.4) to replicate the performance of a PCM layer even if this is not directly modelled as such because of the limitations of the simulation environment.

A crucial aspect is always the attention that must be paid to the physical phenomena considered, and the experimental validation (especially when the simulation strategy includes the use of non-validated, already implemented sub-routines). These kinds of models usually require the Temperature–Enthalpy curve, the thermal conductivity, and the specific heat of the PCM as input data. These models are application oriented and integrated in Building Energy Simulation (BES) software, and are primarily developed for the application of PCMs in opaque building elements.

3.1 OVERVIEW OF MODELS

Most of the models that simulate the PCM behaviour in building envelopes analysed or presented in this paper are implemented in TRNSYS (59%), followed by ESP-r (18%), EnergyPlus (9%), IDA-ICE (9%), and IES-VE (5%) (Fig. 1).

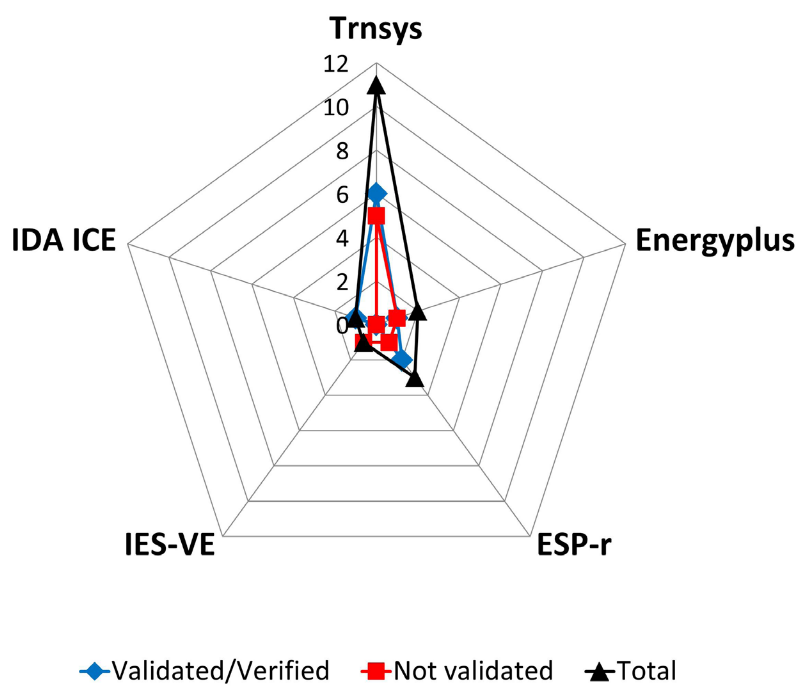


FIG. 1 PCM models implemented in BES software

Most of the analysed models are based on the enthalpy method or the effective heat capacity method (Fig. 2). Regarding the capability to simulate additional physical phenomena, most of the models do not include any additional capability. Six of them are capable of simulating hysteresis; two are capable of simulating subcooling; and none is capable of simulating natural convection inside the PCM (Fig. 2).

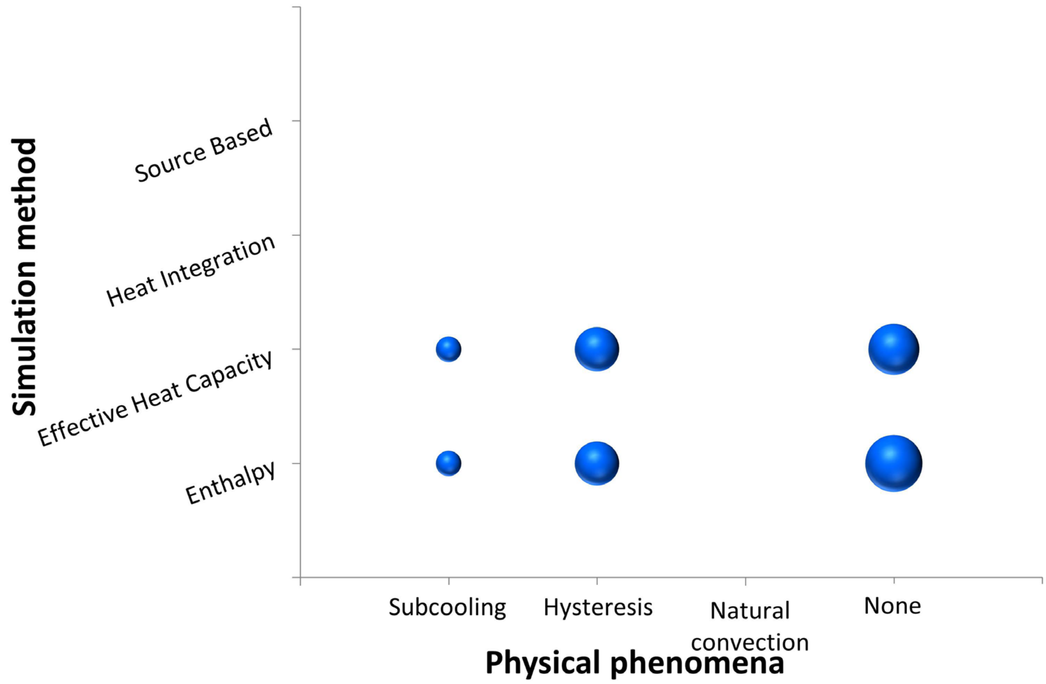


FIG. 2 Simulation method used and physical phenomena considered in PCM models

3.2 TRNSYS

Several PCM modelling efforts have been proposed for TRNSYS in the period 1991-2010 (Ghoneim, Klein, & Duffie, 1991; Stritih & Novak, 1996; Lamberg, Jokisalo, & Sirén, 2000; Jokisalo, Lamberg, & Sirén, 2000; Koschenz & Lehmann 2004; Ibañez, Lázaro, Zalba, & Cabeza, 2005; Ahmad, Bontemps, Sallée, & Quenard, 2006; Schranzhofer, Puschnig, Heinz, & Streicher, 2006; Kuznik, Virgone, & Johannes, 2010; Dentel & Stephan, 2010). Most of these were 1-D models based on finite difference and enthalpy methods. They were compiled in the form of several Types in TRNSYS (Type58, Type 204, Type 232, Type 101, Type 241, and Type 260, Type 399). All were proposed for PCM walls or ceilings and only a few included validations with experimental data. Only two included subcooling (Type 204) or hysteresis effects (Type 399).

In 2014, (Lu, Liu, Huang, & Kong, 2014) developed a new type to simulate PCM in walls. The model is one-dimensional and uses the Finite Volume Method. The apparent specific heat capacity method is used to simulate the PCM behaviour. Hysteresis can also be taken into account; however, convection within the PCM cannot be simulated, nor phase change in microcapsules. Although an experimental validation was performed, significant differences between the numerical and the experimental results were observed.

In 2015, Al-Saadi and Zhai (2015a) used different approaches to model PCM in walls: enthalpy method, heat capacity method, and heat source method, using as solvers the Gauss-Seidel and the TDMA methods and also considering some correction steps. The model is one-dimensional and a fully implicit scheme is used with a spatial discretisation based on the finite volume method. After experimental validation, they concluded that only two schemes out of the eight developed could be considered as potential candidates for integrating into whole building simulation tool: the linearised enthalpy method with the iterative correction scheme and the hybrid correction scheme.

Later, Al-Saadi and Zhai (2015b) validated the model with experimental data at building level, achieving good accuracy.

In 2017, Delcroix, Kummert, and Daoud (2017) presented a new model implemented in TRNSYS as Type 3258, which was dedicated to modelling phase change materials in building envelopes. The model considered 1-D conduction heat transfer and used an explicit finite-difference method coupled with an enthalpy method to consider the variable PCM thermal capacity. The model included temperature-dependent thermal conductivity and PCM-specific effects like hysteresis and subcooling. The model was verified by comparing results with those of other numerical models, following the approach presented in Haghighat et al. (2013) and Johannes et al. (2011). Results of the verification were successful.

There is no evidence in the literature of the direct modelling of transparent systems incorporating PCMs through TRNSYS. However, a Matlab-based model of a PCM layer within a double skin façade has been coupled with TRNSYS to replicate the behaviour of this advanced façade solution (Elarga et al., 2016; Elarga, Dal Monte, Andersen, & Benini, 2017), though through the so called 'ping-pong' coupling that Hensen (1999) implemented by means of Type 155. Furthermore, given the possibility to compile a deliberate Type, it seems reasonable to expect that a dedicated Type could be developed in the future, based on the different numerical models available in literature for PCM glazing systems, as explained in the simulation requirements section.

3.3 ENERGYPLUS

A new approach to simulate PCM in walls in EnergyPlus was studied by Barbour and Hittle (2006). Conduction Transfer Functions (CTF) were used to implement a numerical model for annual simulations, requiring less calculation capacity. The model was one dimension and was based on an ASHRAE Toolkit. The model was validated with real data from previous experiments, but when implemented in EnergyPlus, the simulations showed unacceptable errors when using PCM.

In 2007, a new improved version of EnergyPlus was presented, incorporating the capability to simulate PCM in building envelopes (Pedersen, 2007) in 1-D. To solve the limitations of CTF to simulate PCM, a new implicit finite difference thermal model of building surfaces was incorporated into EnergyPlus, making it possible to use temperature dependent thermal properties. The model simulates the performance of PCMs using the enthalpy method. Later on, in 2012, (Tabares-Velasco et al. 2012) presented a validation of the EnergyPlus model to simulate PCM in walls. The procedure used was the one proposed by ASHRAE Standard 140, consisting of analytical verification, comparative testing, and empirical validation. Two bugs were identified and fixed, providing EnergyPlus with a validated PCM model.

In version 8.8 of EnergyPlus, released in 2017, a dedicated module was first integrated in the simulation code to model hysteresis phenomena. However, such a sub-routine was only applicable to building envelope systems fully realised with PCMs (i.e. not to multilayer walls), making it, in practice, of little or no use. This limitation has been overcome with the latest release of EnergyPlus (v. 8.9) in March 2018 (EnergyPlus, 2018). Alternative approaches to model hysteresis with EnergyPlus includes the use of the Energy Management System module in EnergyPlus (Goia, Chaudhary, & Fantucci, 2018) to impose a different enthalpy-temperature curve depending on the direction of the phase change (i.e. whether melting or solidifying).

As far as the simulation of PCM layers in transparent components is concerned, the literature review reveals no example of models or approaches developed in the EnergyPlus environment. The so-called Conditioned Cavity Method (Kendrick & Walliman, 2007), which is explained in more detail in Section 3.4, might be used in combination with EMS functions and glass panes characterised by (controllable) dynamic optical properties, as a suitable strategy to carry out this modelling. However, the complexity of such an approach would probably be very high and some intrinsic limitations in EnergyPlus might limit the verifications of the results too.

Preliminary attempts to overcome the current limitations of EnergyPlus were made by one of the authors, by connecting an Matlab/Simulink based model with EnergyPlus for co-simulation through the use of the external interface's Building Controls Virtual Test Bed (BCVTB) as well as the Functional Mock-up Units (EnergyPlus, 2015). However, in both cases the two coupled models solve the two sets of partial differential equations using a fixed synchronisation time step, which means that there is no iteration between the two simulation environments. This 'ping-pong' coupling may limit the reliability of the results for a system where inertial effects are crucial.

Given the open-source nature of EnergyPlus, the implementation of custom model in the source code of the simulation environment is a feasible option. This might be a more suitable solution for expanding EnergyPlus's capabilities in simulating a transparent PCM-based layer than the co-simulation approach – though such an activity would require a significant programming effort resulting in the compilation of an entirely new code for the software.

3.4 ESP-R

In 2004, Heim and Clarke (2004) developed a modified ESP-r program to simulate PCM-impregnated gypsum plasterboard. Using control volumes, the effective heat capacity method and assuming equivalent homogeneous properties of PCM-gypsum composite, several temperatures were studied. Unfortunately, the numerical model was not validated with real data and further macro-scale experiments are necessary. On the other hand, Schossig, Henning, Gschwander, & Haussmann (2005) developed an ESP-r model to simulate micro-encapsulated PCM in gypsum wallboard and experimentally validated the model.

In terms of ESP-r's prediction capability when it comes to effects such as hysteresis and subcooling, it must be mentioned that a dedicated subroutine (SPMCMP56) was programmed by Gelissier (2008) and included the possibility to model hysteresis, using the modelling approach developed by Hoffmann (2006).

Later, an experimental validation of the ESP-r PCM model was carried out by Fallahi, Shukla, & Kosny (2012), using a base case wall assembly experimentally tested in the Oak Ridge National Lab. testing facility located in Charleston, South Carolina, and by Heim and Wieprzkowicz (2016), which instead followed the methodology from the International Energy Agency (IEA) Annex 23 by Johannes et al. (2011).

There is no evidence in the literature about the use of ESP-r to simulate transparent envelope applications of PCM system. As for EnergyPlus, possible paths to enable simulation of PCM transparent system with ESP-r include the development of a dedicated subroutine, as well as the adoption of strategies (e.g. the conditioned cavity method) to work around the limitation of the current state of the software tool.

3.5 IES-VE

IES-VE (which stands for Integrated Environmental Solutions) does not incorporate, for the time being, any direct modelling possibility for PCM-based components (either in opaque or in transparent building envelope components). However, a successful work-around, using the ApacheSim model, was developed in the past few years, and the official support of the code (IES-VE 2018) recommends it – though highlighting some limitations.

This work-around is based on the so-called 'Conditioned cavity method' (Kendrick & Walliman, 2007), and is based on the modelling of the PCM layer as a virtual cavity, which is maintained at a set-point temperature corresponding to the nominal melting temperature of the PCM by means of an ideal heating and cooling system. Such a cavity has an infinitesimal volume, whose surface have (almost) no thermal resistance and no heat capacity, while the cavity boundaries themselves have a thermal resistance equal to that of the PCM layer. The equivalent heat capacity method is embedded in this approach.

The complexity of this work-around lies in the fact that the control of the energy to be delivered or removed (through an airflow) in the virtual cavity requires an iterative process to determine the schedule to control the fictitious heating and cooling system. This means that, in practice, due to the need to establish a very detailed control schedule, simulations are often limited to short periods (in the range of one or few weeks).

Favoino (2015) employed the "Conditioned cavity method" in IES-VE by choosing to control the air temperature of the virtual cavity and assuming an infinite latent heat storage capacity for the PCM layer. If, on the one hand, such an approach enables longer simulations to be carried out, on the other hand it requires further verification to be carried out (i.e., the energy balance on the fictitious PCM layer needs to be carried out to ensure that the sum of the virtual cavity's heating and cooling loads, at least on a daily basis, needs to be equal or lower than the actual latent heat storage capacity of the PCM layer.

Other examples of implementation of this method in IES-VE are reported in Padovani Jensen, and Hes (2010) and Ahmed, Mateo-Garcia, McGough, Caratella, and Ure (2018). However, it must be stated that there is no evidence in the literature about the validation of the simulation results obtained though this work-around in IES-VE. It is also not possible to find an application of this approach for transparent PCM-based envelope components.

3.6 IDA ICE

Until recently, IDA-ICE had not supported an open, direct modelling of PCM layers. The new explicit module to model PCM has been now (early 2018) embedded in the latest version 4.8 of this tool. Documentation on this new approach is not yet publicly and fully available, and this prevents a comprehensive understanding of the features of the modelling strategy implemented in the code, which, anyway, seems to be based on the enthalpy method equation.

This new integrated solution is based on a custom model, developed by the software house of IDA-ICE, but until version 4.7 was made available only for research purposes. In 2017 and 2018, Cornaro, Pierro, Puggioni, and Roncarati, (2017) and Cornaro, Pierro, Roncati, and Puggioni (2018) tested and compared the 'PCM wall' module, written in Neutral Model Format language (NMF, the programming language of IDA-ICE), with experimental data. This custom mode simulates the behaviour of a PCM layer based on the enthalpy method with a finite difference method, where one node represents the PCM layers and two nodes are placed a the two interfaces of the PCM, one at each surface of the layer. This model and implements two enthalpy-temperature curves, which may better replicate the behaviour of PCMs with strong hysteresis effects. On the contrary, no evidence is found to assess whether or not subcooling can be addressed. The validation of the model was done using paraffin wax as PCM, a type of PCM that shows little hysteresis and almost no subcooling.

A custom model for transparent PCM layers was developed and validated by (Plüss et al. 2014), and used to estimate the effect of PCM transparent glazed system by (Bionda, Kräuchi, Plüss, & Schröcker 2015). This model is the only model known to replicate PCM in transparent envelope components that is integrated (though through a custom version) in software for BES. The model, written in NMF, uses a 1-D formulation, and is aimed at accurately representing subcooling effects (as it was developed to reproduce the behaviour of a salt hydrate-based system), based on the equivalent capacity method. The optical part of the model is based on the work of Weinläder (2003) and Weinläder et al. (2005).

Since only recently, and primarily through custom releases, IDA-ICE is presently the only tool capable of addressing both opaque and transparent building envelope components that integrate PCMs. However, the potentials and limitations of the implemented simulation codes have not been extensively communicated and a comprehensive validation effort might be necessary to fully demonstrate the reliability of these codes.

4 VALIDATION OF PCM MODULES OR APPROACHES FOR BES TOOLS

Validation of numerical models is crucial to ensure accuracy, precision, and reliability of simulation results. Validation is usually referred to direct comparison between experimental data and simulation results by means of concepts as average errors or relative maximum errors. However, other processes can also be used, such as analytical validation and model verification. Analytical validation consists of comparing the simulation results of a simple case with its analytical solution, while model verification consists of comparing the simulation results with those of a validated model.

In a validation process, experimental errors must be considered, as well as errors in input data. When simulating PCM in building façades, errors in ambient conditions and in PCM thermo-physical properties are of great importance and must be carefully evaluated (Dolado, Lázaro, Marín, & Zalba, 2011). Moreover, special attention must be paid to the physical phenomena modelled, since some physical phenomena of the PCM may not be captured by the model, such as hysteresis or subcooling, and thereby affecting the accuracy of the results.

For validation processes, the variable to be analysed must be determined with care. When modelling PCM, this variable can be a PCM variable (energy stored/released, PCM temperature evolution, etc.) or a variable of the system (internal temperature of the building, energy demand of the building, etc.). When the validation process includes the system (latter case), errors from the PCM model can be hidden by the system.

Finally, when using PCM as a passive system (intrinsic control), one must remember that errors in the system model may result in incorrect temperature predictions of the PCM, thus predicting a complete different behaviour.

In the IEA Annex 23 (Johannes et al. 2011; Haghighat et al. 2013), a standardised procedure for validation of PCM-enhanced (opaque) walls was proposed. This procedure, based on nine different cases, allows a numerical benchmark of the simulation results to be established. On the contrary, and probably due to the limited amount of research activities in this field, as well as the limited market-ready solutions, no standardised procedures have been internationally agreed upon for the validation of PCM-enhanced transparent/translucent elements, where the role of the impinging solar radiation becomes very relevant (Grynning et al. 2013). Thus, a standardised procedure for PCM model validation in general is still required, based on detailed and reliable experimental data.

BES programs usually attempt to experimentally validate their models (Kuznik & Virgone, 2009; Kuznik et al. 2010; Tabares-Velasco, 2012). However, these validations can be limited to certain situations and thus, attention must be paid to the validity range and conditions. From all of the presented models, 10 out of 18 (56%) were validated (Fig. 1). On the other hand, from the most recent models developed, three models in TRNSYS have been validated (Kuznik et al., 2010; Al-Saadi & Zhai, 2015a; Al-Saadi & Zhai 2015b; Delcroix et al., 2017). On the other hand, the model in EnergyPlus is also validated (Tabares-Velasco et al., 2012). A model in ESP-r (Fallahi et al., 2012; Heim & Wieprzkowicz, 2016) and a model in IDA-ICE (Cornaro et al., 2017; Cornaro et al., 2018) were also validated against experimental data.

The model developed by Kuznik et al. (2010) used experimental results from a test cell to compare both the internal ambient temperature and the internal surface temperatures for two external temperature evolutions (step and sinusoidal). For the internal air temperature, maximum differences between numerical and experimental results were 1.1°C and 0.8 °C for step and sinusoidal external temperature evolution, respectively. On the other hand, mean differences were 0.2°C and 0.3°C, respectively. For the internal surface temperature, the model presents good agreement for the step case (maximum difference of 1.1°C and mean difference of 0.2°C). For the sinusoidal case (maximum difference of 1.3°C and mean difference of 0.6°C), the model predicts the same behaviour for all walls, while experimental results demonstrate some differences that are not captured by the model. Although the model shows good agreement with the experimental results, there exist some differences, which can be caused by the aeraulic effects inside the test cells, which cannot be predicted by the model. This limitation could be overcome if the convective heat transfer coefficient is known.

Regarding the EnergyPlus model, the validation procedure performed by Tabares-Velasco et al. (2012) consisted of the analytical verification, comparative verification, and empirical validation of three PCM applications: PCM distributed in drywall, PCM distributed in fibrous insulation, and thin concentrated PCM layers. The analytical verification consisted of solving the Stefan problem. The three cases analysed showed similar results and were in good agreement with the analytical. However, results determined that the node spacing must be smaller (3 times smaller) than the default one in EnergyPlus. The verification process consisted of a comparative testing relative to the ideal PCM model in Heating 7.3, thus representing a more realistic case. Results were in good agreement when time steps where shorter than 4 minutes. Moreover, the PCM model also determined peak load reduction and shift accurately. Finally, experimental validation was performed based on data from the literature (Haavi Gustavsen, Cao, Uvsløkk, & Jelle 2011; Cao et al., 2010). Results were in good agreement in terms of temperature for the heating process, but significant differences were observed for cooling. This is due to the incapability of EnergyPlus to simulate PCM hysteresis, at least until the implementation of this feature in version 9, which was recently tested against dedicated experimental data (Goia et al. 2018). In this latter activity, it was shown that even if the capability to simulate the hysteresis has been embedded in the code, the reliability of the simulation to catch this phenomenon is still pretty low, especially in the case when the melting or solidification process is not completed.

Al-Saadi & Zhai (2015a) also used data from (Cao, 2010) to experimentally validate their models. They used the Root Mean Squared Error (RMSE) to analyse the accuracy of the models. Two different points in the PCM layer were analysed. All models except the non-iterative correction scheme showed an error close to or below 0.1°C, which was within the uncertainty range of the experimental equipment. They also performed a comparative analysis with EnergyPlus, analysing the interior and exterior surface temperatures. All models show good agreement with EnergyPlus, showing errors lower than 0.1°C for a duration of 3 minutes. Finally, the same authors (2015b) also validated the model with the experimental data from Kuznik et al. (2010), showing good agreement.

The model developed by Delcroix et al. (2017) was validated following the approach proposed by the International Energy Agency Annex 23 (Johannes et al., 2011; Haghighat et al., 2013). Results were in accordance with the ones from IEA Annex 23, both for the internal and external surface temperatures and for the heat fluxes.

Fallahi et al. (2012) validated the PCM model in ESP-r, against experimental field data obtained from the Oak Ridge National Lab. testing facility located in Charleston, South Carolina (Kośny, 2008; Kośny, Kossecka, & Yarbrough, 2009; Kośny, Kossecka, Brzezinski, Tleoubaev, & Yarbrough., 2011). To validate the model, the heat flux across the walls was compared with the measured one, showing a total heat gain difference of about 0.6%.

Cornaro et al. (2017) compared the simulation results obtained with IDA-ICE with temperature data collected by means of solar test boxes. These are boxes with a linear scale factor of 1:5 and a surface scale factor of 1:25 with respect to a real room, with five opaque walls and one glazed wall, where the opaque walls are equipped with PCM layers. The results of the validation show that the RMSE, calculated for the indoor air temperature over a period of 3 days, was in the range 1.6 to 1.8 °C, corresponding to an error of ca. 5%.

5 LIMITATIONS AND DESIRABLE FURTHER IMPROVEMENTS

The use of PCM in building envelopes has focused in passive systems (intrinsic control systems), where the PCM is passively charged and discharged by either solar energy/external temperature or an internal heat source. The main goal of such systems is to reduce the energy demand of the building and/or improve the thermal comfort. However, these systems present difficulties in their design process and PCM selection, since they require very specific designs to achieve a suitable performance. For operating conditions (weather conditions, use and occupation of the building, etc.) different from the design ones, the behaviour of the PCM will change, and its phase change temperature may no longer be suitable, thus reducing or even eliminating its benefits.

Moreover, errors in the building model affect the PCM behaviour, and may result in inaccurate PCM system design (such as phase change temperature) that may reduce its benefits.

Additionally, the recharging of the PCM is sometimes limited in such applications, compromising the potential benefits of the system. Therefore, active systems (extrinsic control systems) are advisable in order to solve some of these problems.

Finally, other important issues in the simulation of the PCM remain to be solved. The accurate inclusion of hysteresis, subcooling, natural convection, and ageing in PCM simulation must be solved in future BES tools. Although some advances have been done in the newest versions of software tools, there is still room for improvement.

6 CONCLUSIONS AND FUTURE WORKS

This paper provides an overview of the successful implementation of the modelling and simulation of PCM-based building envelope systems in software tools for building energy simulation (BES). Five of the most common BES tools have been analysed and evidence from the scientific literature about their use for simulating PCM-enhanced envelope has been given.

In a time when the integration of detailed aspects typical of PCMs' behaviour (i.e. hysteresis and subcooling) is becoming more and more common in BES tools, it is necessary to highlight how validation of the models implemented in BES is probably an underestimated activity. Although there have been proposals on standardised procedures, these have not been extensively used, and the comparison of the simulation performance of BES has not been comprehensively carried out – at least as far as the latest developments are concerned. An overall comparison of the performance of BES tools in modelling and simulation of PCM-enhanced envelope would definitely be an important research task to fill a present-day knowledge gap. Coupling such a numerical benchmarking with reliable experimental activities would further increase the relevance of the effort. Apart from the standardised procedures proposed by the IEA Annex 23 for model verification (Johannes et al., 2011; Haghighat et al., 2013), two different sets of experimental data have been used in the literature for experimental validation of different models (Kuznik et al., 2010; Cao, 2010).

While almost all the BES tools analysed in this paper allow the simulation of opaque envelope systems incorporating PCMs to be carried out (and, with the help of a work-around, such a simulation is possible with all of them), it is almost impossible at present to simulate the transparent envelope, which includes PCMs exposed to solar radiation – only one custom model is available for one software tool. Modelling and simulation of transparent solutions incorporating PCMs is therefore way behind the simulation of opaque PCM envelope, and future development of tools by the BES community should also focus on enabling this simulation domain.

Acknowledgements
The authors would like to thank EU Cost Action TU1403 'Adaptive Facades Network' for providing excellent research networking. The authors Albert Castell and Marc Medrano would like to thank the Catalan Government for the project grant (2017 SGR 659) given to their research group. The author Francesco Goia would like to thank the Research Council of Norway and several partners through The Research Centre on Zero Emission Buildings (ZEB) (2009 – 2017, grant 193830) at the Norwegian University of Science and Technology.

References

Ahmad, M., Bontemps, A., Sallée, H., & Quenard, D. (2006). Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material. *Energy and Buildings 38*, pp.673–681.

Ahmed, A., Mateo-Garcia, M., McGough, D., Caratella, K., & Ure, Z. (2018). Experimental evaluation of passive cooling using phase change materials (PCM) for reducing overheating in public building. *E3S Web of Conferences 32*, 01001, 1-7. doi: 10.1051/e3sconf/20183201001

Alexides, V., & Solomon, A.D. (1993). Mathematical Modeling of Melting and Freezing Processes. Washington: Hemisphere Publishing Corporation, p. 47.

Al-Saadi, S.N., & Zhai, Z. (2015). Systematic evaluation of mathematical methods and numerical schemes for modeling PCM-enhanced building enclosure. *Energy and Buildings 92*, pp.374–388.

Al-Saadi, S.N., & Zhai, Z. (2015). A new validated TRNSYS module for simulating latent heat storage walls. *Energy and Buildings 109*, pp.274–290.

Andersen, M., Roecker, C., & Scartezzini, J. L. (2005). Design of a time-efficient video-goniophotometer combining bidirectional functions assessment for transmission and reflection. *Solar Energy Materials and Solar Cells 88(1*), 97-118. Doi: 10.1016/j.solmat.2004.10.009

Barbour, J.P., & Hittle, D.C. (2006). Modeling Phase Change Materials With Conduction Transfer Functions for Passive Solar Applications. *Transactions of the ASME Vol. 128,* February 2006.

Bianco, L., Cascone, Y., Goia, F., Perino, M., & Serra, V. (2017a). Responsive glazing systems: Characterisation methods and winter performance. *Solar Energy, 155*, pp.372–387.

Bianco, L., Cascone, Y., Goia, F., Perino, M., & Serra, V. (2017b). Responsive glazing systems: Characterisation methods, summer performance and implications on thermal comfort. *Solar Energy, 158*, pp.819–836.

Bionda, D., Kräuchi, P., Plüss, I., & Schröcker, M. (2015). Simulation of the thermal performance of translucent phase change materials and whole-building energy implications. *Proceedings of 10th Conference on Advanced Building Skins*. doi: 10.13140/RG.2.1.1729.4806

Bony, J., & Citherlet, S. (2007). Numerical model and experimental validation of heat storage with phase change materials. *Energy and Buildings, 39(10),* pp.1065-1072.

Cabeza, L.F., Castell, A., Barreneche, C., de Gracia, A., & Fernández, A.I. (2011). Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews 15*, pp.1675–1695. doi:10.1016/j.rser.2010.11.018.

Cabeza, L.F. (Ed.) (2015) *Advances in Thermal Energy Storage Systems. Methods and Applications*. Woodhead Publishing. United Kingdom. ISBN: 978-1-78242-088-0.

Cao, S., Gustavsen, A., Uvsløkk, S., Jelle, B.P., Gilbert, J., & Maunuksela, J. (2010). The effect of wall-integrated phase change material panels on the indoor air and wall temperature - Hot box experiments, In: *Zero emission buildings - Proceedings of renewable energy conference 2010*. Trondheim, Norway. p. 15-26.

Cao, S. (2010) *State of the Art Thermal Energy Storage Solutions for High Performance Building*. Department of Physics, University of Jyväskylä, Finland,2010.

Cornaro, C., Pierro, M., Puggioni, V.A., & Roncarati, D. (2017). Outdoor Characterization of Phase Change Materials and Assessment of Their Energy Saving Potential to Reach NZEB. *Buildings 7(3*), p.55. doi: 10.3390/buildings7030055

Cornaro, C., Pierro, M., Roncati, D., & Puggioni, V. (2018). Validation of a PCM Simulation Tool in IDA ICE Dynamic Building Simulation Software Using Experimental Data from Solar Test Boxes. *Proceedings of Building Simulation Application (BSA) 2017.* Bolzano University Press, Bolzano, pp.159-166.

de Gracia, A., Navarro, L., Castell, A., Ruiz-Pardo, A., Álvarez, S., & Cabeza, L.F. (2013). Thermal analysis of a ventilated facade with PCM for cooling Applications. *Energy and Buildings 65,* pp.508–515. doi.org/10.1016/j.enbuild.2013.06.032.

de Gracia, A., Navarro, L., Castell, A., & Cabeza, L.F. (2015a). Energy performance of a ventilated double skin facade with PCM under different climates. *Energy and Buildings 91,* pp.37–42. doi.org/10.1016/j.enbuild.2015.01.011.

de Gracia, A., Fernández, C., Castell, A., Mateu, C., & Cabeza, L.F. (2015b). Control of a PCM ventilated facade using reinforcement learning techniques. *Energy and Buildings 106,* pp.234–242. doi.org/10.1016/j.enbuild.2015.06.045.

Delcroix, B., Kummert, M., & Daoud, A. (2017). Development and numerical validation of a new model for walls with phase change materials implemented in TRNSYS. *Journal of Building Performance Simulation 10 (4)*, pp.422-437.

Dentel, A., & Stephan, W. (2010, December). Thermal comfort in rooms with active PCM constructions. *8th International Conference on System Simulation Buildings, Liege* pp.13-15.

Dolado, P., Lázaro, A., Marín, J.M., & Zalba, B. (2011). Characterisation of melting and solidification in a real scale PCM-air heat exchanger: Numerical model and experimental validation, *Energy Conversion and Management 52 (4),* pp.1890-1907. doi.org/10.1016/j.enconman.2010.11.017.

Elarga, H., Goia, F., Zarrella, A., Dal Monte, A., & Benini, E. (2016). Thermal and electrical performance of an integrated PV-PCM system in double skin façades: A numerical study. *Solar Energy 136*, pp.112-124.

Elarga, H., Dal Monte, A., Andersen, R.K., & Benini, E. (2017). PV-PCM integration in glazed building. Co-simulation and genetic optimization study. *Building and Environment 126*, pp.161-175

EnergyPlus (2015). *External Interface(s) Application Guide.*

EnergyPlus (2018). *Engineering Reference (v. 8.9).*

Fallahi, A., Shukla, N., & Kosny, J. (2012) Numerical thermal performance analysis of PCMs integrated with residential attics. *Fifth National Conference of IBPSA-USA*, Wisconsin.

Fantucci, S., Goia, F., Perino, M., & Serra, V. (2018). Sinusoidal response measurement procedure for thermal performance assessment of PCM by means of Dynamic Heat Flow Meter Apparatus. Submitted for publication in Energy and Buildings.

Favoino, F. (2015). Assessing the performance of an advanced integrated facade by means of simulation: The ACTRESS facade case study. *Journal of Facade Design and Engineering 3,* pp.105–127. doi: 10.3233/FDE-150038

Geissler, A. (2008). *SPMCMP56 subroutine in ESP-r Source Standard Code* (software code).
Ghoneim, A.A., Klein, S.A., & Duffie, J.A. (1991). Analysis of collector-storage building walls using phase-change-materials. *Solar Energy Vol. 47*, No. 3, pp. 237-242.
Giovannini, L., Goia, F., Lo Verso, V.R.M., & Serra, V. (2017). Phase Change Materials in glazing: implications on light distribution and visual comfort. *Energy Procedia 111,* pp.357–366
Goia, F., Perino, M., & Haase, M. (2012). A numerical model to evaluate the thermal behaviour of PCM glazing system configurations. *Energy and Buildings 54,* 141–153
Goia, F., Perino, M., & Serra, V. (2014). Experimental analysis of the energy performance of a full-scale PCM glazing prototype. *Solar Energy 100*, pp.217–233.
Goia, F., Zinzi, M., Carnielo, E., & Serra, V. (2015). Spectral and angular solar properties of a PCM-filled double glazing unit. *Energy and Buildings 87,* pp.302–312.
Goia, F., Chaudhary, G., & Fantucci, S. (2018). Modeling and experimental validation of an algorithm for simulation of hysteresis effects in phase change materials for building components. *Energy and Buildings 174*, pp.54–67.
Gowreesunker, B.L., Stankovic, S.B., Tassou, S.A., & Kyriacou, P.A. (2013). Experimental and numerical investigations of the optical and thermal aspects of a PCM-glazed unit. *Energy and Buildings* 61, pp.239–249.
Grynning, S., Goia, F., Rognvik, E., & Time, B. (2013). Possibilities for characterization of a PCM window system using large scale measurements. *International Journal of Sustainable Built Environment 2,* pp.56–64.
Günther, E., Mehling, H., & Hiebler, S. (2007). Modeling of subcooling and solidification of phase change materials. *Modelling Simulation in Material Science and Engineering, 15(8),* pp.879-892.
Haavi, T., Gustavsen, A., Cao, S., Uvsløkk, S. & Jelle, B.P. (2010). Numerical simulations of a well-insulated wall assembly with integrated phase change material panels - Comparison with hot box experiments, In: *The international conference on sustainable systems and the environment; 2011.* Sharjah, Sharjah, United Arab Emirates.
Haghighat, F., Yu, Z., Inard, C., Michaux, G., Kuznik, F., Johannes, K., Virgone, J., Barzin, R., Farid, M., Bastani, A., Stathopoulos, N., Mankibi, M. E., Nkwetta, D. N., Moreau, A., Vouillamoz, P-E., Castell, A., Adl-Zarrabi, B. (2013). *Annex 23: Energy storage in buildings of the future - Applying Energy Storage in Ultra-low Energy Buildings.* Paris, France: International Energy Agency.
Heim, D., & Clarke, J.A. (2004). Numerical modelling and thermal simulation of PCM–gypsum composites with ESP-r. *Energy and Buildings 36,* pp.795–805.
Heim, D., & Wieprzkowicz, A. (2016). Positioning of an Isothermal Heat Storage Layer in a Building Wall Exposed to the External Environment. *Journal of Building Performance Simulation 9 (5*), pp. 542–554.
Hensen, J.L.M. (1999). A comparison of coupled and de-coupled solutions for temperature and air flow in a building. *ASHRAE Transactions 105 (2),* pp.962–969.
Hoffmann, S. (2006). *Numerische und experimentelle Untersuchung von Phasenübergangsmaterialien zur Reduktion hoher sommerlicher Raumtemperaturen* [Numerical and experimental investigation on phase change materials to reduce high indoor temperatures during summer]. (Doctoral thesis) Bauhaus-Universität, Weimar, Germany.
Hu, H., & Argyropoulos, S.A. (1996). Mathematical modelling of solidification and melting: a review. *Modelling Simulation Material Science and Engineering 4,* pp.371–396.
Ibáñez, M., Lázaro, A., Zalba, B., & Cabeza, L.F. (2005). An approach to the simulation of PCMs in building applications using TRNSYS. *Applied Thermal Engineering 25*, pp.1796–1807.
Ishimaru, A. (1978). Wave propagation and scattering in random media. In*: Single Scattering and Transport Theory, 1*. California, USA: Academic Press.
Johannes, K., Virgone, J., Kuznik, F., Wang, X., Haavi, T., & Fraisse, G. (2011). *Annex 23: Applying Energy Storage in Buildings of the Future - Development of Sustainable Energy Storage Designs for a variety of Ultra-low energy building thermal, phase change materials and electrical storage options.* Paris, France: International Energy Agency.
Jokisalo, J., Lamberg, P., & Sirén, K. (2000). *Thermal simulation of PCM structures with TRNSYS.* Stuttgart, Germany: Terrastock 2000.
Jones, R.W., Balcomb, J.D., Kosiewicz, C.E., Lazarus, G.S., McFarland, R.D., & Wray, W.O. (1982). *Passive solar design handbook. Volume 3: Passive solar design analysis.* Boulder, CO: U.S. Department of Energy ASES,
Kendrick, C., & Walliman, N. (2007). Removing unwanted heat in lightweight buildings using phase change materials in building components: Simulation modelling for PCM plasterboard. *Architectural Science Review 50(3),* pp.265-273.
Koschenz, M., Lehmann, B. (2004). Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings. *Energy and Buildings 36*, pp.567–578.
Kośny, J. (2008). Field Testing of Cellulose Fiber Insulation Enhanced with Phase Change Material‖. *Oak Ridge National Laboratory report- ORNL/TM-2007/186,* September 2008.
Kośny, J., Kossecka, E., & Yarbrough, D. W. (2009). Use of a Heat Flow Meter to Determine Active PCM Content in an Insulation. *Proceedings of the 2009 International Thermal Conductivity Conference (ITCC) and the International Thermal Expansion Symposium (ITES*) – August 29 - September 2, 2009 Pittsburgh, PA, USA.
Kośny, J., Kossecka, E., Brzezinski, A., Tleoubaev, A., & Yarbrough, D. (2011). Numerical and Experimental Thermal Analysis of PCM-Enhanced Insulations. *International Thermal Conductivity Conference (ITCC)* - June 26 - 30, 2011 Saguenay, QC, Canada.
Kośny, J. (2015). PCM-Enhanced Building Components. An Application of Phase Change Materials in Building Envelopes and Internal Structures. Springer International Publishing, doi:10.1007/978-3-319-14286-9.
Kuznik, F., Virgone, J., & Johannes, K. (2010). Development and validation of a new Trnsys Type for the simulation of external building walls containing PCM. *Energy and Buildings 42(7*), 1004-1009. doi.org/10.1016/j.enbuild.2010.01.012.
Lamberg, P., Jokisalo, J., & Sirén, K. (2000). The effects on indoor comfort when using phase change materials with building concrete products. *Proceedings of Healthy Buildings 2000*, Vol. 2, pp. 751–756, SIY Indoor Air Information OY.

Li, D., Ma, T., Liu, C., Zheng, Y., Wang, Z., & Liu, X. (2016). Thermal performance of a PCM-filled double glazing unit with different optical properties of phase change material. *Energy and Buildings 119*, pp.143–152.

Liu, C., Zhou, Y., Li, D., Meng, F., Zheng, Y., & Liu, X. (2016). Numerical analysis on thermal performance of a PCM-filled double glazing roof. *Energy and Buildings 125*, pp.267-275.

Lu, S., Liu, S., Huang, J., & Kong, X. (2014). Establishment and experimental verification of PCM room's TRNSYS heat transfer model based on latent heat utilization ratio. *Energy and Buildings 84*, pp.287–298.

Manz, H., Egolf, P., Suter, P., & Goetzberger, A. (1997). TIM–PCM external wall system for solar space heating and daylighting. *Solar Energy 61*, pp.369–379.

McKellar, B.H.J., & Box, A.M. (1981). The scaling group of radiative transfer equation. *Journal of Atmospherical Science 38*, pp.1063–1068.

Mehling, H., & Cabeza, L. F. (2008). Heat and cold storage with PCM, An up to date introduction into basics and applications, Berlin Heidelberg: Springer-Verlag.

Navarro, L., de Gracia, A., Colclough, S., Browne, M., McCormack, S.J., Griffiths, P., & Cabeza, L.F. (2016a). Thermal energy storage in building integrated thermal systems: A review. Part 1. active storage systems. *Renewable Energy 88*, pp.526-547. doi.org/10.1016/j.renene.2015.11.040.

Navarro, L., de Gracia, A., Niall, D., Castell, A., Browne, M., McCormack, S.J., Griffiths, P., & Cabeza, L.F. (2016b). Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system. *Renewable Energy 85*, pp.1334-1356. doi.org/10.1016/j.renene.2015.06.064.

Padovani, R., Jensen, C., & Hes, D. (2010). Approach to thermal modelling innovative green building elements: Green roof and phase change plasterboard. AUBEA 2010 - Proceedings of the 2010 conference of the Australasian Universities Building Education Association, 2010, 1 (1), pp. A080, 1 - 17

Pedersen, C.O. (2007). Advanced zone simulation in EnergyPlus: Incorporation of variable properties and Phase Change Material (PCM) capability. *Proceedings of Building Simulation 2007.*

Plüss, I., Kräuchi, P., Bionda, D., Schröcker, M., Felsenstein, S., Zweifel, G. (2014). Modellbildung eines Phasenwechsel-fassadenelements in IDA-ICE [Modelling of a facade element with phase change in IDA-ICE]. *Proceedings of BAUSim: Fifth German-Austrian IBPSA Conference RWTH Aachen University*, 1166, p.1-5.

Schossig, P., Henning, H.M., Gschwander, S., & Haussmann, T. (2005). Micro-encapsulated phase-change materials integrated into construction materials. *Solar Energy Materials & Solar Cells 89*, pp.297–306.

Schranzhofer, H., Puschnig, P., Heinz, A., & Streicher, W. (2006). Validation of a TRNSYS simulation model for PCM energy storages and PCM wall construction elements. *ECOSTOCK 2006 - 10th International Conference on Thermal Energy Storage.* Pomona, NJ, USA.

Silva, T., Vicente, R., & Rodrigues, F. (2016) Literature review on the use of phase change materials in glazing and shading solutions. Renew. Sustain. Energy Rev. 53, 515–535.

Stritih, U., & Novak, P. (1996). Solar heat storage wall for building ventilation. *Renewable Energy 8* (1-4), pp.268-271.

Tabares-Velasco, P.C., Christensen, C., Bianchi, M. (2012). Verification and validation of EnergyPlus phase change material model for opaque wall assemblies. *Building and Environment 54*, pp.186-196. doi.org/10.1016/j.buildenv.2012.02.019.

Vigna, I., Bianco, L., Goia, F., & Serra, V. (2018). Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis. *Energies 11*, p.111. doi:10.3390/en11010111

Voller, V.R. (1997). An overview of numerical methods for solving phase change problems, in Minkowycz, W.J. and Sparrow, E.M. (Eds), *Advances in Numerical Heat Transfer, Vol. 1*, Basingstoke: Taylor & Francis,

Weinläder, H. (2003). *Optische Charakterisierung von Latentwärmespeichermaterialien zur Tageslichtnutzung* [Optical characterization of phase change materials for daylighting]. (Dissertation) Julius-Maximilians-Universität, Würzburg, Germany.

Weinläder, H., Beck, A., & Fricke, J. (2005). PCM-facade-panel for daylighting and room heating. *Solar Energy 78*, pp.177–186.

Study of a BIPV Adaptive System: Combining Timber and Photovoltaic Technologies

Enrico Sergio Mazzucchelli[1*], Mark Alston[2], Marcin Brzezicki[3], Luisa Doniacovo[4]

* Corresponding author
1 Politecnico di Milano, enrico.mazzucchelli@polimi.it
2 University of Nottingham
3 Wrocław University of Science and Technology
4 General Planning srl

Abstract
The paper presents the first results of research that was partly conducted within the framework of European COST Action TU1403 – Adaptive Façades Network, on the development of an adaptive BIPV (Building Integrated Photovoltaic) solution able to change its curvature in relation to the external environmental conditions, orientating itself in order to optimise the energy production without the aid of any mechanical and electrical systems. After analysing the characteristics of the main adaptive materials that are currently used for such applications, the contribution outlines the main features of the proposed system, which consists of thin film solar cells coupled with a thin layer of hygromorphic material, manufactured from two wooden slats joined together and produced from different types of wood and trunk cuts. The hygromorphic layer thus obtained can change its shape as a function of temperature and relative humidity of outdoor conditions, thanks to the different expansion coefficients of the two wooden slats. To evaluate the performance of the component, three shape configurations for the adaptive strips have been assumed. For each hypothesis, the lamellae have been modelled using the Rhinoceros 5 Software, according to the curvatures taken during the different months of the year. The Rhino models have been imported into Autodesk Ecotect Analysis to calculate the incident solar radiation and to study the self-shadowing effect in the various configurations (in relation to the climatic conditions of the city of Milan). The paper outlines the system and PV energy production optimisation process, as well as possible applications in the field of façade design.

Keywords
adaptive façades, adaptive component, hygromorpic materials, BIPV technology, wood, timber

DOI 10.7480/jfde.2018.3.2602

1 INTRODUCTION

The building envelope has a dominant impact on a building's energy balance and it plays an essential role towards meeting the nearly Zero Energy Buildings (nZEB) target (International Energy Agency 2013; European Commission 2013). Nowadays, however, it is increasingly recognised that more flexible behaviour of the façade is desirable (Loonen, Rico-Martinez, Favoino, Brzezicki, Menezo, La Ferla, & Aelenei, 2015; Andresen, Kleiven, Knudstrup, & Heiselberg, 2008; Schumacher, Schaeffer, & Vogt, 2010; Wiggington & Harris, 2002). Adaptive façades should provide controllable insulation and thermal mass, daylighting, solar shading, ventilation and humidity control, etc. Moreover, these façades should collect and convert available renewable energy (mainly solar) in an adaptive way, in order to follow, as far as it's possible, the building's energy needs (Luthander, Widén, Nilsson, & Palm, 2015). Facing the challenges of decarbonisation for the building sector in the EU (a target of 80% for 2050), the building envelope should integrate active functions relating to energy production (collect, convert, store, distribute). In this regard, building façades are often the largest potential surface for integration of renewable energy generation components (photovoltaic, solar thermal, etc.) in urban areas.

The envelope adaptivity can be summarised by many concepts. Considering the way adaptive façade components are controlled/operated, terminology such as that in Loonen, Trčka, Cóstola, and Hensen (2013) is used: intrinsic control implies that it is self-adjusting, since the adaptive behaviour is automatically triggered by environmental stimuli, which allows for low-cost operation and maintenance. On the other hand, extrinsic control first implies the retrieval and processing of information and then, actions to be taken. This allows for feedback and, thus, for artificial intelligence. These components rely on technologically-imposed intelligence (Holstov, Bridgens, & Farmer, 2015) enabled by the application and interaction of sophisticated mechanical and electronic sensors, control systems, and actuators, which results in a dependency on energy supply, high complexity and cost, and potential reliability and maintenance issues (Holstov et al., 2015).

2 THE BIPV ADAPTIVE SYSTEM

The aim of the research method is to advance the design of an innovative BIPV (Building Integrated Photovoltaic) façade system with standardised components that are available on the market. The proposal investigated suitable materials and associated elements that could be used to progress the research into a functional demonstrator, to determine a solution that is capable of self-orientation in response to solar radiation at differing solar elevation angles during the year in an intrinsic way, without the need of an energy supply. The BIPV component consists of thin film solar cells coupled with a hygromorphic material layer (Fig. 1). The component was analysed and modelled to determine: geometry, self-shadowing effects, and energy production, using Rhinoceros 5, Autodesk Ecotect Analysis, and Microsoft Excel software. The climate data considered in the modelling phase was provided by ARPA (Regional Agency for Environmental Protection) Lombardia, over a 5-year time span.

Other factors were considered in terms of: mechanical resistance, component interface details design, production, assembly, and durability to assess life cycle. This progress would hence develop system optimisation as a complete concept, without ignoring the construction and installation issues, which will affect integration with a building envelope, if adopted for future application. Other research application methods have been developed: lamellae lightness, for example, which allows a moveable system that responds to daylight changes. However, these systems require significant substructures that limit geometry scale, the requirement of energy, and the associated high cost of installation and ongoing maintenance issues (Doniacovo, 2016).

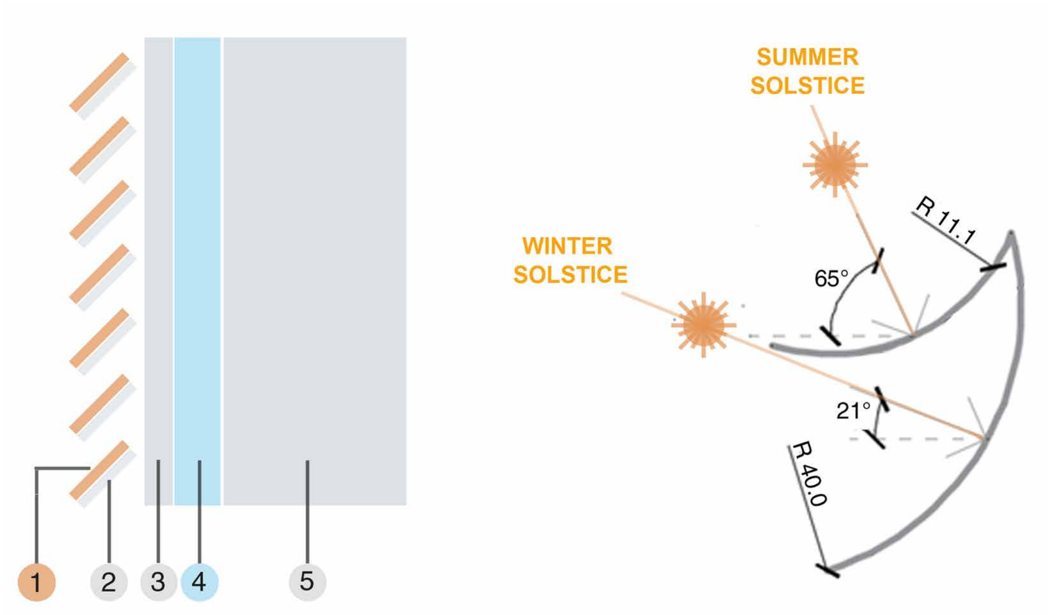


FIG. 1 Façade functional layers: 1 – Energy capture layer, 2 – Hygromorphic layer, 3 – Substructure layer, 4 – Ventilation gap, 5 – Other wall layers (structure, thermal insulation, etc.). Example of lamellae curvature (on the right)

3 THE BIPV ADAPTIVE LAYER

Hygromorphic materials (HMs), thermo-bimetals (TBs), shape memory alloys (SMAs), and shape memory polymers (SMPs) were considered to develop the research proposal. HMs are moisture sensitive and their behaviour and properties are determined by their configuration (single layer, bi-layer, thickness, fibres orientation, etc.) and production conditions (Holstov et al., 2015; Mazzucchelli & Doniacovo, 2017). TBs are the result of coupling two materials with different properties; if subjected to thermal load they modify their length causing the inflection of the coupled element. SMAs consist of at least two metal elements and have the ability to regain a previous geometrical form after being subjected to a thermal load. SMPs will change in geometrical shape (deformed) state if subjected to an applied thermal load that is different to that of their rest state (permanent form).

Hygromorphic materials have lower mechanical strength, however the aesthetic qualities, life cycle sustainability, and a lower production cost give them interesting characteristics. TBs exceed the limit of the mechanical strength typical of HMs, but they may cause overheating problems that should be avoided in the PV component layer. The behaviour of SMAs and SMPs can be controlled efficiently with respect to outdoor conditions. However, they are expensive and their production scale range limits the range of items (mostly springs or wires). For these reasons, it was decided to use HMs for the lamellae adaptive layer, consisting of two wooden strips, one active and one passive, joined together.

For successful application of the proposed solution, key values will determine the effectiveness of operation that is dependent on seasonal changes of temperature and relative humidity. These two factors affect the moisture content of HMs, which in turn influences the component dynamic movement behaviour. The analysis was carried out with respect to the climatic conditions of the city of Milan (Italy), latitude of 45 ° N, characterised by a moderate continental climate, with cold and damp winters and hot and sultry summers.

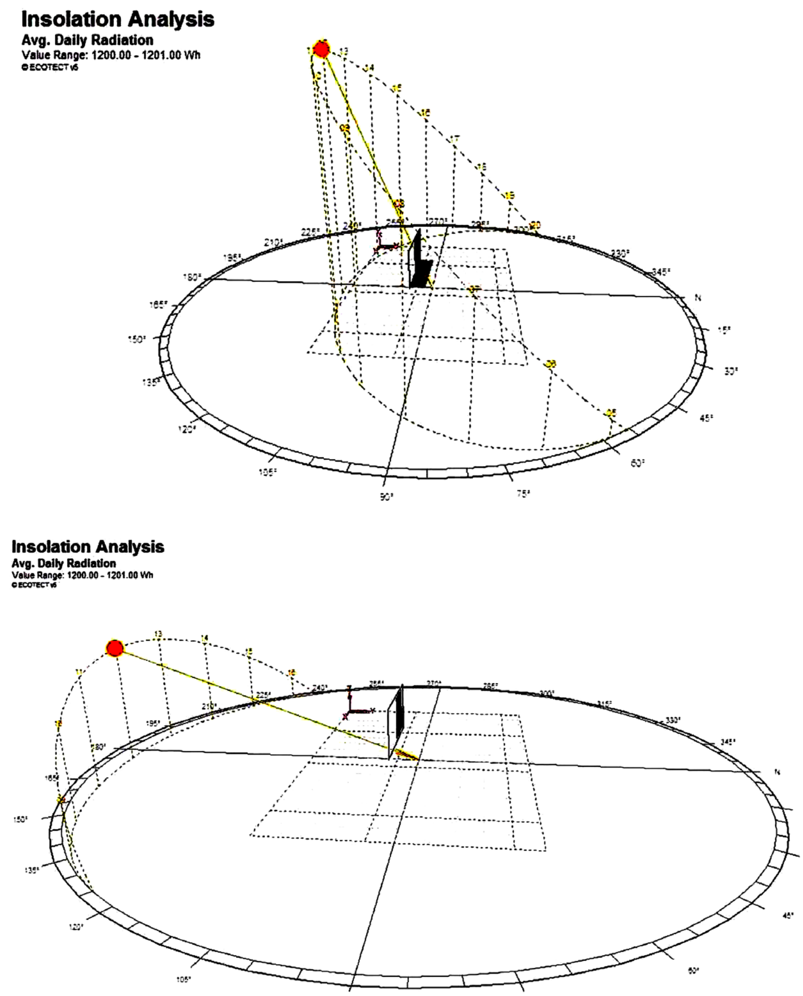


FIG. 2 Solar height in summer (21st June) and winter (21st December)

Optimisation in the geometrical form of the adaptive layer, is determined through two parameters: lamellae inclination with respect to the vertical plane and associated curvature. These parameters will orient the geometrical configuration to solar radiation inclination for maximisation of solar capture. The analysis was carried out on the surfaces exposed to the east, south, and west (only the methodology and results for the south-facing surfaces are presented in this paper). This was evaluated by a software tool, Ecotect 'Insolation Analysis'. This analysis determined optimal solar elevation angles in the summer and winter solstices as illustrated in Fig. 2. The outcome of this approach indicated the following optimum inclination values for the lamellae: β = 65° for the summer solstice; β = 21° for the winter solstice; while the optimal radius of curvature are R = 11.1 cm and R = 40.0 cm, respectively (see Fig. 1).

The maximum and minimum bending radii for the lamellae were calculated using the formulae proposed by Holstov et al. (2015), where the response of a hygromorphic material is a function of the effective moisture content change, that is, the difference in moisture content in the wood and associated species, which in turn depends on air temperature and Relative Humidity (RH). This response is a function of the dimensional variations of the two timber layers that are used to produce the composite material lamella form. The maximum curvature is obtained using rotary-cut strips and placing the active layer in such a way that the direction of the curvature is orthogonal to that of the timber grain. It is necessary to exclude timber species with inversions of grain and timber grain defects, due to the associated effects on layer curvature.

Timber material thickness and stiffness ratios will affect the active movement of the passive layer and hence the selection of layering combinations, as indicated in Fig. 3. The factors ‘m’ and ‘n’ are related to the choice of the optimal thickness ratio between the active and passive layers, ensuring that the curvature change coefficient ‘f’ is the maximum obtainable. Four hypotheses of active/passive layer combination have been considered (Table 1).

HYPOTHESIS	ACTIVE LAYER MATERIAL	PASSIVE LAYER MATERIAL	$N=E_P/E_A$	$M=T_P/T_A$
1	Wooden sheet	Wooden sheet	15-20	0.25
2	Wooden sheet	GFRP polymer	3-5	0.50
3	Wooden sheet	PET polymer	15-40	0.20
4	Wooden sheet	PC polymer	15-40	0.20

TABLE 1 Stiffness ($n=E_p/E_a$) and thickness ($m=t_p/t_a$) ratio values (a=active, p=passive)

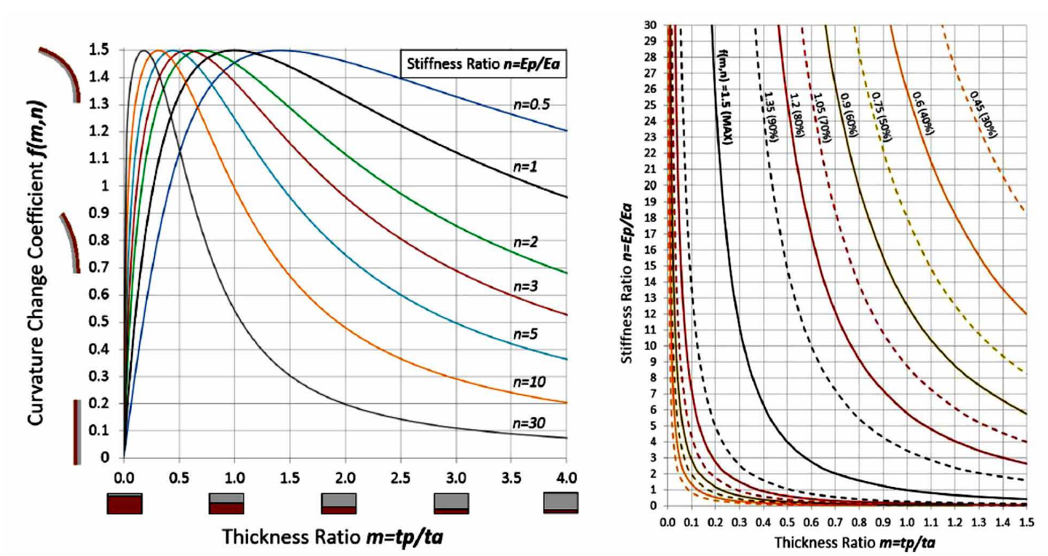


FIG. 3 Relations between curvature change coefficient and stiffness and thickness ratio *(Holstov et al., 2015)*. The factors ‘m’ and ‘n’ are related to the choice of the optimal thickness ratio between active and passive layer, ensuring that the curvature change coefficient ‘f’ is the maximum obtainable.

Results indicate that curvature is inversely proportional to the total thickness. For this reason, increased thickness of the active layers in a composite approach will enhance the response to long-term climate changes. However, reduction in the timber layer depth of the active layers will react to changes on an hourly basis. On the other hand, the thickness also affects other aspects of the lamellae: insufficient thickness can result in excessive deformations under the wind action, lower resistance to weathering, and lower fire resistance. The results demonstrate that the lamellae angles of bending by different material configuration can be calculated and compared to an optimal choice for the combination of materials.

HYPOTHESIS	MOUNTAIN MAPLE	BLACK WALNUT	WHITE BIRCH	EUROPEAN BEECH	OAK	SIBERIAN LARCH
1	139.3	146.6	130.7	108.2	109.6	131.8
2	141.3	147.1	129.1	106.5	108.0	131.3
3	157.3	165.1	149.4	125.1	126.5	149.7
4	160.6	170.0	157.0	132.4	133.6	155.4

TABLE 2 Obtainable radius of curvature R [mm] (21st of June, t_a = 4mm, R_0 = 450 mm)

The results (Table 2) show that the summer optimal curvature (R = 111 mm) can be obtained using beech or oak lamellae coupled with another timber or GFRP (Glass Fibre Reinforced Polymer) layer. The ideal winter curvatures are not strictly defined, but summer presented the optimal conditions for performance that was considered preferable (Doniacovo, 2016). The initial curvature in a summer thermal load was determined by K = 1/450 mm-1 to reach the desired bending radius in the summer period, maintaining adequate thicknesses to satisfy the other performance targets. The component durability and resistance under atmospheric conditions was evaluated according to UNI EN 350, UNI EN 355, and UNI EN 460 standards, and to the guidelines developed within the European WoodExter project, ‘Service life and performance of exterior wood above ground’ (2012). The results indicated an oak wood configuration as the desired species as a solution that gave better resistance to biological attack and was more highly sustainable (Mazzucchelli & Doniacovo, 2017).

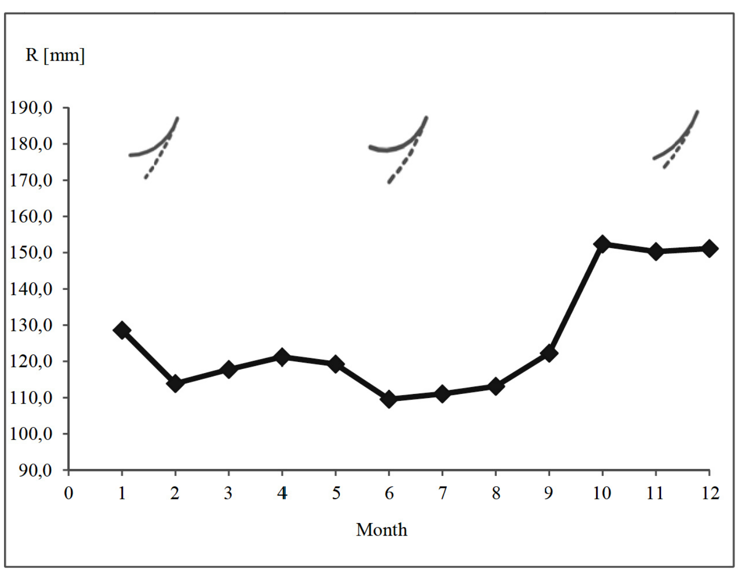


FIG. 4 Example of monthly average oak lamellae curvatures (active layer: 4 mm thickness, R_0=450mm)

From the modelling results (Fig. 4), it can be noted that during the summer months the lamellae monthly average curvature is rather important, so that the component, if located on a south-facing façade, can capture the sun's rays with higher solar elevation angles. From October to January the curvature is not marked, and this allows the same component to capture the sun's rays with low elevation angles.

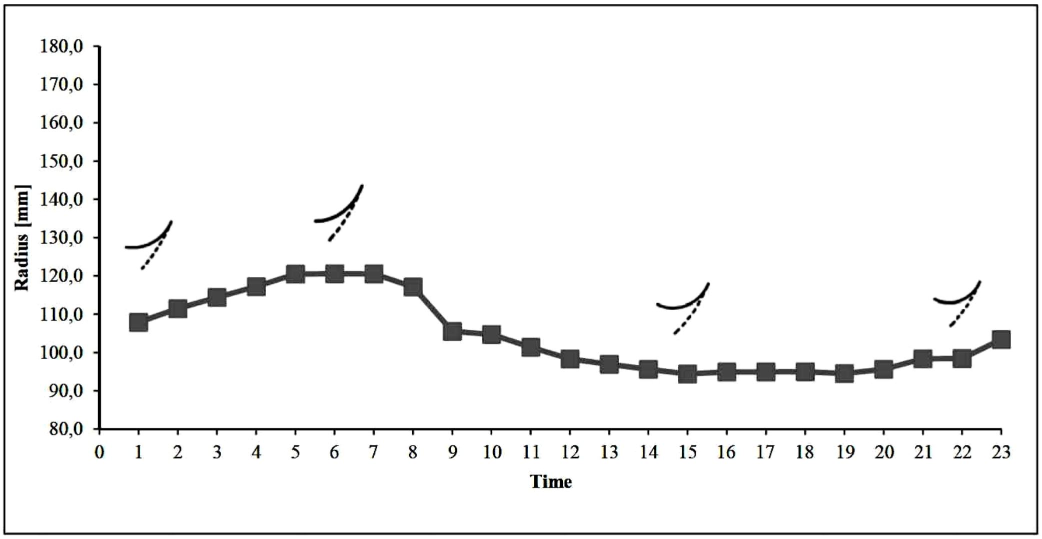


FIG. 5 Example of daily variation of the curvature radius – 21st June

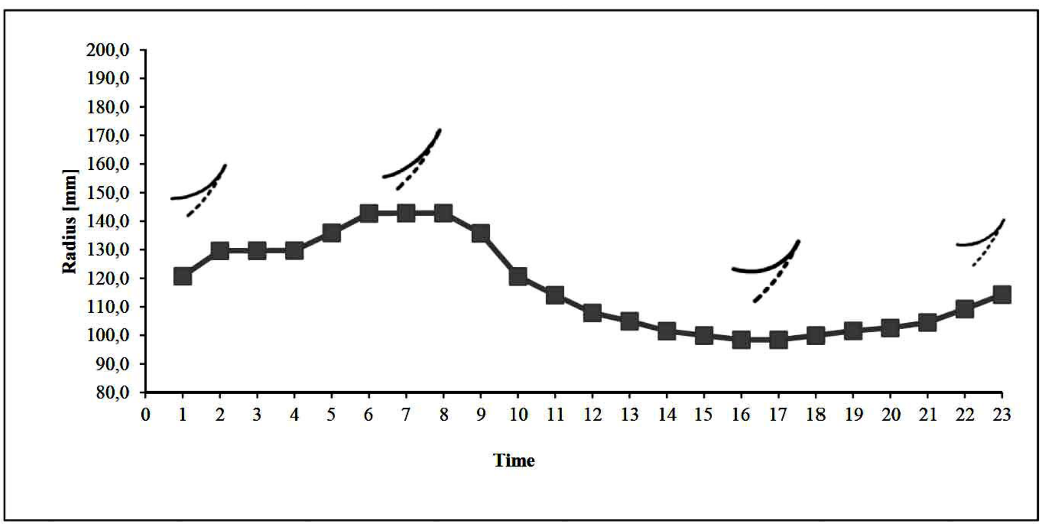


FIG. 6 Example of daily variation of the curvature radius – 21st September

The daily behaviour of the lamellae was also analysed. Using the formulae proposed by Holstov et al. (2015), and assuming that the HMs can adapt instantly to the climate conditions, the curvature for each hour of the day was calculated. From the analysis carried out, it can be noted that the lamellae are in a "closed" configuration overnight and the associated bending movement increases in response to solar orientation over time. In this regard, the component shows a dynamic behaviour that allows it to adapt to the sunlight height on the horizon, not only referring to seasonal changes, but also referring to a single day. In any case, over the course of a single day, the curvature remains rather unchanged for long periods of time, with a radius that, for example, varies from 98mm (12.00 am) to 94mm (6.00 pm) in June (Fig. 5), and from 107mm (12.00 am) to 99mm (6.00 pm) in September (Fig. 6).

Compared to the monthly average curvature used to verify the component's performance, in these periods the radius deviates by about 4-8mm, a deviation that is considered acceptable for the energy analysis. This was associated with the proposed lamellae of increased depth to the active layer (4mm) and their dimensional variations are decidedly slower than those studied by Holstov et al. (2015). The lamellae thickness is therefore adequate to achieve the monthly and seasonal performance targets (Mazzucchelli & Doniacovo, 2017) as well as to withstand weather actions.

Lastly, because the lamellae are subject to repeated deformation cycles, the connection between the active and passive layers should be sufficiently resistant to transfer the shear stress between the two layers, but also flexible enough to bend repeatedly without damaging themselves. For this particular use, an epoxide adhesive was chosen.

4 PHOTOVOLTAIC LAYER AND ENERGY ANALYSIS

The energy capture layer surface consists of photovoltaic modules. Among the currently used PV modules, the most efficient are the mono- or polycrystalline types. However, these types of module can't be used in the proposed system because of their rigidity, which would prevent the lamellae from changing shape to follow the dimensional variations in tracking the sun path. Hence, flexible solutions include thin amorphous silicon film and organic photovoltaic cells. Both have lower efficiency in comparison to crystalline silicon, but they perform better in diffuse light conditions and have an associated increased life cycle sustainability (Tress, 2014; Mazzucchelli, 2013). For this application, thin film photovoltaic cells (0.2 mm thickness, with a weight of 0.28 kg/sqm) were chosen. They can be easily fixed by adhesives and it is even possible to fasten or rivet them to the most varied material surfaces. These cells are embedded in two ethylene tetrafluoroethylene (ETFE) films (Mazzucchelli & Doniacovo, 2017). In order to evaluate the performance of the component, three lamellae shape configurations, covering a surface of 60x75cm, were analysed (Fig. 7):

- rectangular 15x60cm, organised in parallel rows;
- rectangular 15x10cm, organised in parallel rows and with an offset of half their height;
- rhomboidal 15x15cm, organised in parallel rows and with an offset of half their height.

Geometry façade form lamellae were independently modelled using the software, Rhinoceros 5.
To evaluate curvature surfaces (as described in Section 3), the incident solar radiation values on the different lamellae configurations were compared with those obtainable with respect to a vertical surface and a flat lamellae configuration with a fixed inclination of 43° with respect to the vertical plane (see Fig. 8). This inclination value represents the average of the optimal values during the summer and the winter solstice in Milan.

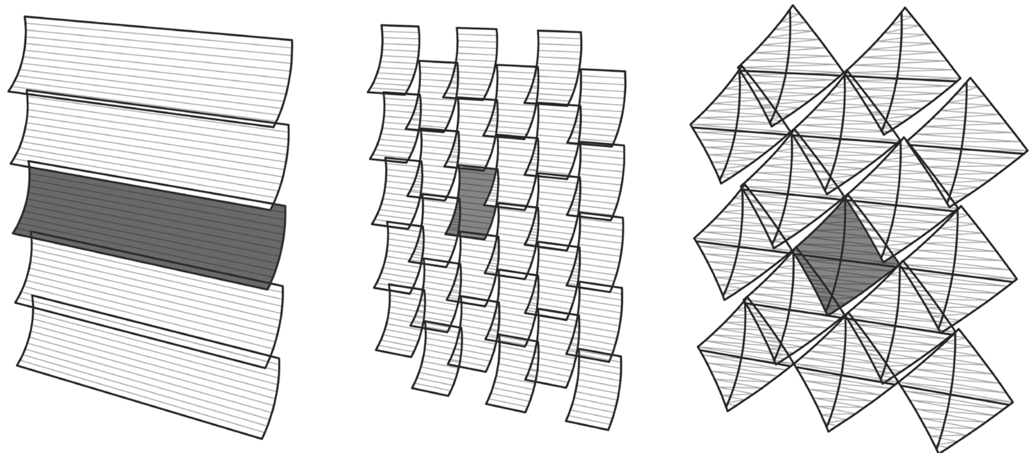


FIG. 7 Lamellae configurations: rectangular 15x60cm, rectangular 15x10cm, rhomboidal 15x15cm. The dark lamellae are those which were analysed.

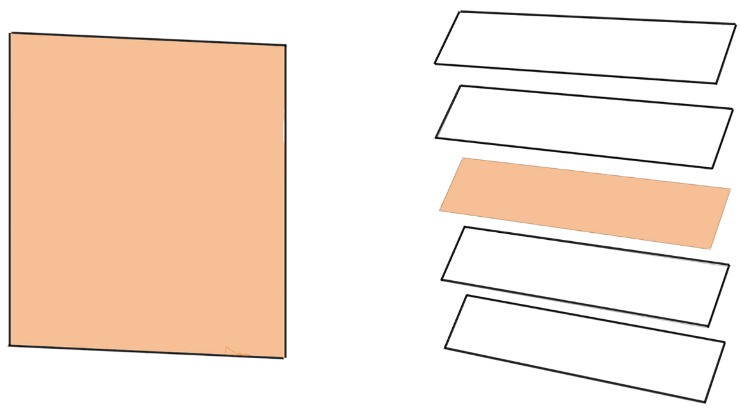


FIG. 8 Lamellae comparison models: vertical surface (on the left) and flat flakes with 43° inclination

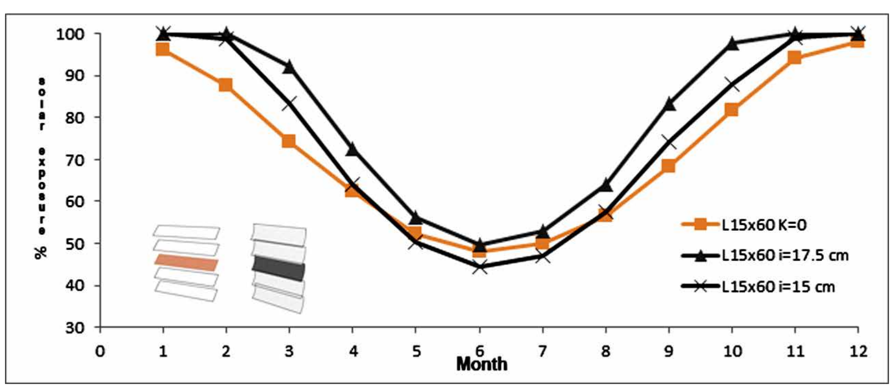


FIG. 9 Percentage of lamellae area exposed to the sun monthly. The effect of the adaptive layer can be noted.

The Rhino models were imported into Autodesk Ecotect Analysis to calculate the incident solar radiation and to study the self-shadowing effect in the different lamellae configurations. The first analysis studied the shadows in order to choose the optimal shape of the lamellae and the optimal distance between rows. Through the 'Shading Analysis, Overshadowing and Sunlight Hours' options, the modelling was set for a specific period according to daily average radiation values. Subsequently, the calculation was extended to each month, taking care to associate to each month the corresponding lamellae monthly average curvature.

From the performed modelling, it's possible to note (for example, in Fig. 9 15x60cm lamellae) that in all configurations solar radiation exposure is higher during winter, due to the low solar declination, and it decreases as it approaches the summer solstice, when the sun is at the highest point on the horizon. This is due to the shadow zone in the area close to the substructure. The lamellae that capture more solar radiation are those of 15x60cm in size, whose solar exposure improves greatly if there are spaces of 17.5cm between rows (Fig. 9). The 15x15cm lamellae indicate good performance in terms of the solar radiation capture to orientation. However, they cannot be separated due to aesthetic constructive reasons (Doniacovo, 2016). Lastly, the 15x10cm lamellae show low performance when the rows are at a 15cm spatial configuration, while the behaviour greatly improves if the distance is increased up to 20cm.

A second analysis studies incident radiation on the different lamellae configurations. Through the 'Incident solar radiation' tool, the modelling was set for a specific period. The calculations related to each month, combining the corresponding lamellae curvature. Through values obtained for each infinitesimal analysed surface, an average of the obtained values was calculated. This average was applied to the entire surface of the lamella. The results show that the 15x60cm lamellae with a 17.5cm distance between rows increases the capacity to absorb solar radiation by 14%, when compared to the hypothesis of a vertical surface with the same orientation. The lamellae of 15x60cm in size and a distance between rows of 15cm provide a light increase (equal to 1.01%). However, 15x10cm lamellae show a decrease of 11%. Such a reduction in performance can be attenuated to the spacing of the lamellae rows with a distance of 20cm or 25cm. In these cases, the increase in performance is 4.89% and 17% respectively, but the 25cm distance configuration is not recommended for aesthetic reasons (because the substructure is visible). Lastly, the 15x15cm lamellae show a slight decrease in performance when compared to a vertical PV surface. However, it is not possible to change the distance between rows for constructive and aesthetic reasons. Fig. 10 indicates incident solar radiation over a period of one year by a demonstrator square meter prototype with variations in differing lamellae typologies. The value for the vertical surface is also shown to allow a comparison among the different configurations.

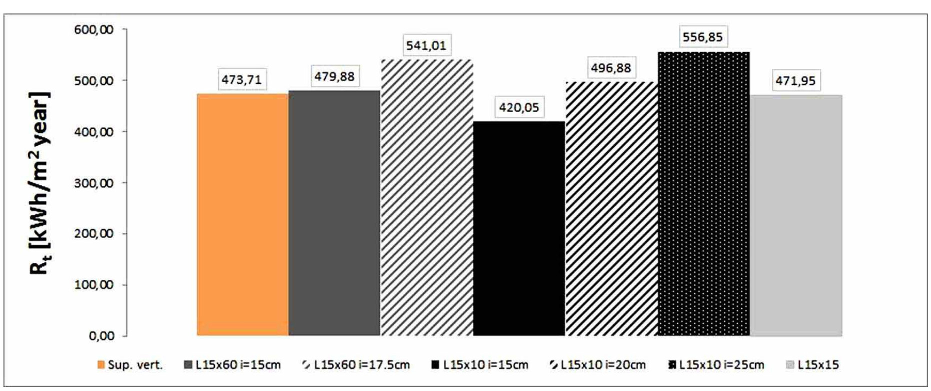


FIG. 10 Incident solar radiation on different kinds of lamellae configurations

The PV energy production analysis (photovoltaic cells efficiency: 8%, balance of system efficiency: 85%) was carried out on two types of lamellae only: the 15x10cm and the 15x60cm ones. First, the case of the15x60cm lamellae was considered. The results obtained are shown in Fig. 11. Increasing the distance between rows up to 17.5cm, the energy production shows an 8% increase when compared to a vertical surface case and a 7.1% increase when compared to the configuration with a distance of 15cm between rows (Mazzucchelli & Doniacovo, 2017). Considering the 15x10cm lamellae, the energy produced does not reach the values obtainable using a vertical PV panel but, considering a distance of 20cm between rows, it is possible to increase the performance by 8.19% when compared to those of 15cm. In this last case, a thin PV foil that is also installed on the vertical surface above the lamellae is considered (see Fig. 13). By further increasing the distance between rows, there are no benefits in terms of energy production and, indeed, the energy produced is lower than that of the 15cm distance configuration.

In conclusion, the higher performance increment is obtained when using 15x60cm lamellae, with a distance of 17.5cm between rows.

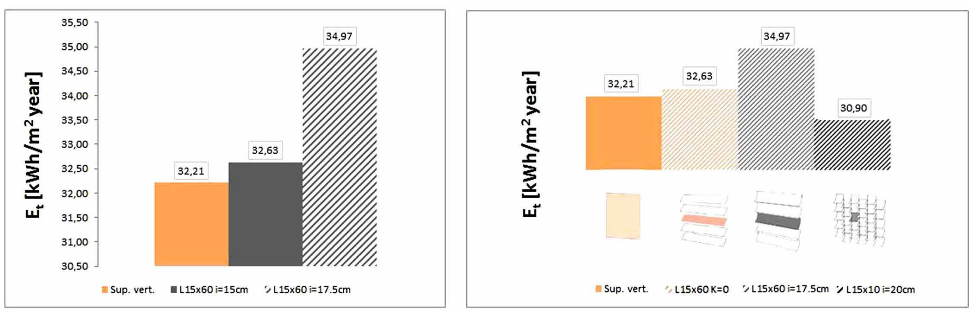


FIG. 11 Energy produced for 15x60cm lamellae (on the left) and comparison between different kinds of lamellae (on the right)

5 BIPV COMPONENT APPLICATION

This solution proposal can be easily integrated into the building envelope and it's applicable at a large-scale level. This implies that cost and technological complexity must be as optimised as possible. The BIPV adaptive lamellae can be installed on a wood frame to create modular panels that can be used as façade cladding (Fig. 13 and Fig. 14) or as a sun-shading system (Fig. 15). The basic preassembled module consists of a wood perimeter frame and transoms, where the lamellae are fastened with screws. Concerning the union between the lamellae adaptive layer and the photovoltaic one, steel male-female screws are used (Fig. 12).

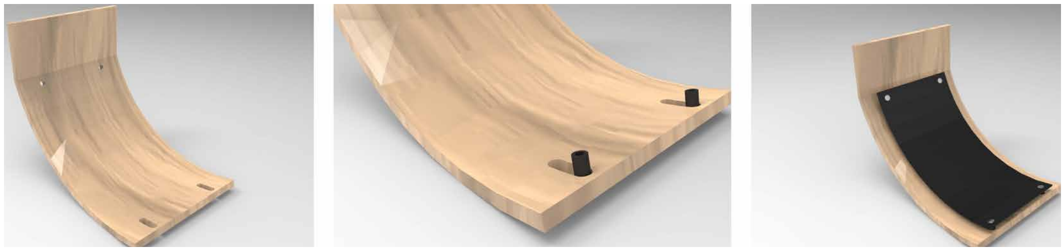


FIG. 12 Lamellae adaptive layer (15x10cm) with fixing holes (on the left). Detail of the slotted holes and the neoprene gaskets (on the centre). Lamellae with adaptive and photovoltaic layer (on the right)

The assembly between the adaptive and the photovoltaic layer allows for adjustment of this last one to the shape taken by the self-adjusting lamella. For this purpose, slotted holes on the lower part of the lamellae have been provided. The male-female screws, inserted into special cylindrical neoprene gaskets, can slide in these holes when the lamella modifies its shape. The position and the different shape of the holes, where the fixing screws are inserted, is illustrated in Fig. 12. This connection allows a 0.5cm back-PV cell ventilation, which also helps to reduce their overheating.

FIG. 13 Renders of 15x10cm (on the left) and 15x60cm lamellae panels (on the centre). Wooden panel substructure detail (on the right)

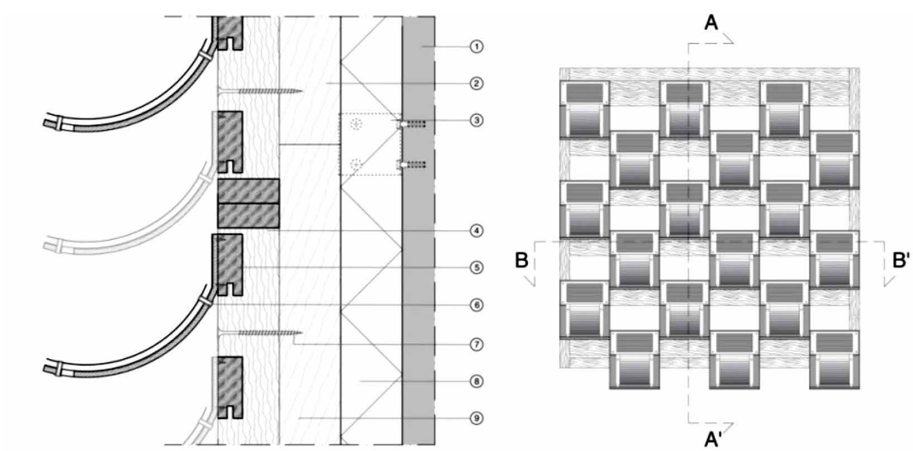


FIG. 14 Detail of the 15x10cm lamellae panel (on the left) and front view of the 60x75cm panel (on the right)

In the sun-shading configuration (Fig. 15), the panels consist of a wooden framework (40x100mm in section) and intermediate transoms, where the lamellae are fastened. In the case of mobile sun-shading, the handling system is made up of steel guides anchored to the upper floor, where sliding carriages, connected to the panels, are inserted. The panels are connected to reels with a manual rewind mechanism with a torsion spring, to move the panels safely and ergonomically. Lastly, the electrical wires that connect the PV cells are inserted into special grooves of the wooden frame profiles.

FIG. 15 Example of BIPV adaptive lamellae integration as façade cladding and as a sun-shading system

6 CONCLUSION

The presented research progresses the design of an adaptive BIPV façade system to be able to self-orientate the photovoltaic layer in an intrinsic way and without the need of any energy supply. To reach this goal, thin film solar cells are coupled with HM layers that respond to changes in environmental humidity by modifying their own curvature. In winter, the hygromorphic layer is designed to be almost vertical, so that the solar cells can receive direct sunlight in a favourable way. In high solar radiation conditions, the lamellae naturally present a higher curvature, orienting the solar cells so as to maximise the production of photovoltaic energy. This solution furthers advances other promising features, including the use of a natural adaptive material such as wood. The energy analysis shows that the lamellae adaptability leads to an increase in the energy production through optimal studied configurations (e.g. the 15x60cm one), when compared to a vertical PV surface or to flat PV tiles with fixed inclination. In this regard, the next step of the research will be the further optimisation of the system geometry and the realisation of a full-scale prototype to verify the model results, as well as to test the lamellae durability, the lamellae repeated deformation cycles effects, and the effective delayed response incidence on the expected performance. Moreover, if the climate does not guarantee significant daily and seasonal changes of relative humidity, the use of different kinds of wood or HMs, reacting to different relative humidity levels, could also be considered and tested.

Acknowledgements

The authors would like to gratefully acknowledge COST Action TU1403 'Adaptive Façades Network' for providing excellent research networking.

References

Andresen, I., Kleiven, T., Knudstrup, M., & Heiselberg, P. (2008*).* Methods and Tools for Designing Integrated Building Concepts*. State-of-the-art Review. Vol. 2B. DCE Technical Report No. 049. International Energy Agency.* Aalborg: Aalborg University.

Doniacovo, L. (2016). *Studio, progettazione e modellazione di un sistema fotovoltaico innovativo integrato nell'involucro edilizio* [Study, design and modelling of an innovative photovoltaic system integrated into the building envelope]. (Master's Thesis). Politecnico di Milano.

European Commission (2013). *Energy-efficient buildings - Multi-annual roadmap for the contractual PPP under Horizon 2020*. Luxembourg: Publications Office of the European Union. doi:10.2777/29993

International Energy Agency (2013). *Technology Roadmap - Energy efficient building envelopes.* Paris: IEA Publications.

Holstov, A., Bridgens, B.N., & Farmer G. (2015). Hygromorphic materials for sustainable responsive architecture. *Construction and Building Materials, 98*, pp.570-582.

Jermer, J. (Ed.). (2012). *WoodExeter - Service life and performance of exterior wood above ground - Final report*. Borås: SP Sveriges Tekniska Forskningsinstitut.

Loonen, R.C.G.M., Rico-Martinez, J.M., Favoino, F., Brzezicki, M., Menezo, C., La Ferla, G., & Aelenei, L. (2015). Design for façade adaptability – Towards a unified and systematic characterization. *Proceedings of the Advanced Building Skins 2015,* 3-4 November 2015, Bern, Switzerland.

Loonen, R.C.G.M., Trčka, M., Cóstola, D., & Hensen, J.L.M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews . 25*, pp.483–493.

Luthander, R., Widén, J., Nilsson, D., & Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy, 142*, pp.80–94.

Mazzucchelli, E.S. (2013). *Edifici ad energia quasi zero – Materiali, tecnologie e strategie progettuali per involucri e impianti innovativi ad alte prestazioni.* [Nearly Zero Energy Buildings - Materials, technologies and design strategies for innovative high performance envelopes and building services]. Maggioli Editore.

Mazzucchelli, E.S., & Doniacovo, L. (2017). The integration of BIPV Adaptive Flakes in the building envelope. *Proceedings of the 12th Conference on Advanced Building Skins,* 2-3 October 2017, Bern, Switzerland.

Schumacher, M., Schaeffer, O., & Vogt, M. (2010). *Move: Architecture in Motion - Dynamic Components and Elements.* Basel: Birkhäuser

Tress, W. (2014). Organic solar cells - Theory, Experiment and Device Simulation. *Springer Series in Material Science, vol.208.*

Wigginton, M., & Harris, J. (2002). *Intelligent Skins*. Oxford: Butterworth-Heinemann.

The Role of Geometry for Adaptability: Comparison of Shading Systems and Biological Role Models

Susanne Gosztonyi[1,2]

* Corresponding author

1 Competence Center Building Envelope, Institute of Civil Engineering, Lucerne University of Applied Sciences and Arts Engineering and Architecture, Technikumstrasse 21, 6048 Horw, Switzerland, susanne.gosztonyi@hslu.ch

2 Architectural Facades and Products Research Group, Design of Construction, Architectural Engineering and Technology, TU Delft, Julianalaan 134, 2628 Delft, The Netherlands

Abstract

Dynamic shading systems represent the majority of realised adaptive façades. It seems that geometrically complex kinetic solutions have increased in recent years, mainly due to the use of parametric design tools and digital production. In most shading systems, however, geometry rarely plays a guiding role in the design. The kinetic mechanisms are confined to linear or planar geometries. Geometry plays an important role in biological organisms, because it is the decisive factor for efficiency and growth. Their growth patterns could provide new insights for dynamic shading designs. For this, spatial morphology criteria for shading systems were identified to obtain criteria directly related to geometry. These were supplemented by criteria on kinetic mechanisms. Then, biological analogies that correlate geometrical structures with adaptability were sought. Using biomimetic methods, particularly from functional morphology, principles in growth patterns were analysed and compared to shading systems. It revealed that the restriction to space, location, and material-inherent properties does not affect the solution diversity, but follows an evolutionary objective: Plants, for example, use ingenious geometrical structures to allow adaptation, mainly over lifetime but also dynamically. Whether these principles can be applied to the design of dynamic shading systems is then discussed. The aim of the paper is to provide impulses for further studies on adaptive shading systems that focus on the innovative use of space with greater flexibility in motion. The overall premise of the paper is to demonstrate the applicability of biomimetic methods for architectural engineering.

Keywords

adaptive facades, shading systems, biomimetics, geometry, growth pattern, kinetic mechanisms, spatial morphology

DOI 10.7480/jfde.2018.3.2574

1 INTRODUCTION

Dynamic shading systems are of particular interest in the framework of energy efficiency strategies in buildings, because the cooling energy demand raises continuously. The research study 'Cost Efficient Solar Shading Solutions in High Performance Buildings' mentions that "dynamic solar shading leads to mean cooling energy savings of more than 36% when averaged across all glazing types and climate conditions in Europe"; and it could increase to 65-70% for South-West orientated facades in central Europe (Hutchins, 2015). Thus, dynamic shading systems seem to be one of the key measures for drastically decreasing the cooling energy consumption of buildings in Europe. However, recent evaluations show that implemented measures with regard to shadings do not show the desired effect (Hutchins, 2015; Werner, 2016). Since there are few studies on the causes, one can only speculate. One obstacle to effectively operating dynamic shading systems may be the conflict of shading versus visual comfort (view out, use of daylight). This affects the energy consumption of artificial lighting during shading periods. The conflict might be solved by the — currently somewhat neglected — design of shading systems. Conventional products show mainly linear and planar geometries with limited adaptive morphology. Since there are few alternatives that are economically feasible and promise a certain robustness, the potential of the geometry of shading surfaces is yet to be explored.

A closer look at the geometrical characteristics of dynamic shading systems raises questions, two of which are discussed in this paper: What role do geometrical patterns play in current shading systems? And, how do spatial morphology criteria and geometrical forms influence the flexibility of adaptation? Ensuring the best possible functionality and adaptability by using geometrical growth patterns is an essential requirement of biological evolution. The systematic search for analogies in nature could show potentials, particularly for the second question, and enable a design shift away from the neglected geometry to innovative shading geometries. The aim of the paper is to present geometrical patterns of conventional shading systems and draw a link to biological role models that deal with surface optimisation strategies through geometry. The goal is also to illuminate the role of geometrical forms for energy efficiency in this context and to stimulate further studies as to whether spatial designability influences functionality.

The paper begins in Section 2 with a description of the applied methodology to identify various geometrical and functional mechanisms and continues in Section 3 with the categorisation of parameters of shading systems that are linked to spatial morphology, in order to deal with the first question. Section 4 deals with the potentials linked to geometrical forms and functions in nature in order to demonstrate the link between geometry and performance optimisation. It also briefly discusses some principles of the identified geometrical peculiarities in order to determine a possible transfer to dynamic shading systems, which addresses the second question. In the conclusion, a hypothesis is put forward in relation to a re-design strategy for dynamic shading systems based on geometrical patterns, which might overcome the conflict between performance and visual quality.

2 METHODOLOGY

The use of biomimetic methods to identify biological potentials for advanced building design is a trend that has been increasing for several years. Within the field of adaptive façades, optimisation investigations on daylight and shading components by applying biomimetic principles are a central topic. Studies on shape morphing solar shadings by Fiorito et al. (2016) and Pesenti, Masera, Fiorito, & Sauchelli (2015) can be cited as exemplary. While many activities focus on the development of new material composites (Lienhard et al., 2011) or design recommendations in a 'biomimetic' manner (Menges, 2012; Al-Obaidi, Ismail, Hussein, & Abdul, 2017), very few studies are targeted at employing biomimetic methods for re-designing or upgrading existing material and system solutions. This work aims to contribute to this objective by presenting some biomimetic principles for the re-design of geometrical forms for effective dynamic shading systems.

As an initial step towards understanding the role of geometry in the adaptive functionality of shading systems, spatial morphology criteria and kinetic patterns of conventional shading systems were developed. These were then assigned to different shading types in order to classify geometrical and motion-related parameters. In the next step, biological role models, showing geometrical and functional dependencies for the given context, were searched by applying the biomimetic analogy method. To understand the relations between patterns/shape, functions, and behaviour of the role models, a combination of methods from functional morphology, the 'structure-form-(behaviour)-function' model (Sartori, Pal, & Chakrabarti, 2010), and underlying physical laws are applied. It is assumed that patterns and forms in nature follow the laws of physics and thus can be (roughly) explained with mathematical formulae (Cohen, Reich, & Greenberg, 2014). Some conclusions about these relations were drawn in this work. While it is already a complex process to understand and abstract biological 'structure-behaviour-function' relationships, some go even one step further towards identifying generic design patterns (Cohen et al., 2014). This intention is also a motivator for this work, which, so far, is only presented as a hypothesis in this paper.

3 SPATIAL MORPHOLOGY OF SHADING SYSTEMS

Dynamic shading systems represent the majority of adaptive façade systems according to case studies in the COST "Adaptive Façade Network" (COST TU1403, 2018) (Loonen, Trcka, Costola, & Hensen, 2013) (Aelenei, Aelenei, & Vieira, 2016). In addition to the many functions that a dynamic shading system must fulfil with regard to aesthetic, visual, thermal, or structural requirements, its adaptability is the most critical task – more so than with any other façade component. In the design phase, however, shading systems are primarily regarded as an intangible factor for overheating or solar gains evaluation. In energetic building performance evaluations, they are considered as a static value or a range of static values representing worst, best, and standard cases. Their optical properties (transparency, reflectance, emissivity), their influence on daylight quality (daylight transmittance, glare protection, visual quality), and their control strategies are taken into account by global data. The role and performance impact of the specific geometry of an element, as well as its related kinetic patterns, is not considered. Few studies have been found during the literature survey for this work that focus on specific physical characteristics related to the (static) geometry of shading elements in order to enable better energy performance (Fiorito et al., 2016) (Cohen et al., 2014) (Pesenti et al., 2015).

3.1 PARAMETERS FOR SPATIAL MORPHOLOGY

Whenever kinetic movements of façade components occur, certain geometrical and mechanical parameters are taken into account to allow a change of state. Scale, size, and positioning of individual components, as well as the spatial extension and modularity of the system, are some of these parameters that have to be considered when designing adaptive (kinetic) shading systems. Some respective criteria were identified from the analysis of the case studies in COST "Adaptive Façade Network" (COST TU1403, 2018) and further developed for a first draft of spatial and kinetic criteria of adaptive facades (Gosztonyi, 2015). They are summarised as "spatial morphology criteria" (Fig. 1). One such criterion is the 'physical impact', which describes the geometrical appearance of the system, such as planar, linear, or polygonal patterns of the surface, and their changing appearance in the several adaptation states. This also describes the kinetic motion along defined axes (one- or multi-axial). The second criteria, 'repetitive structures', describes the geometrical form itself and the modularity of the elements. While most elements are usually standardised (e.g. strip fins, planar textiles), there is no standard solution for freeform and curved elements. Parametric design considerably supports the development of freeform geometries in order to achieve higher motion flexibility (and performative optimisation) (Barozzi, Lienhard, Zanelli, & Monticelli, 2016). The third criteria, 'spatial versality', is linked to the adaptation mechanisms and its space requirements. Being mounted on guiding rails, hinges, or brackets, shading elements cause a spatial intrusion into the third dimension by folding, wrapping, rolling, and shifting, among others. The mechanisms define the kinetic morphology of the system and determine the coverage pattern of the façade surface. This criteria also describes the space that is needed for the motion, which is critical for the choice of the solution.

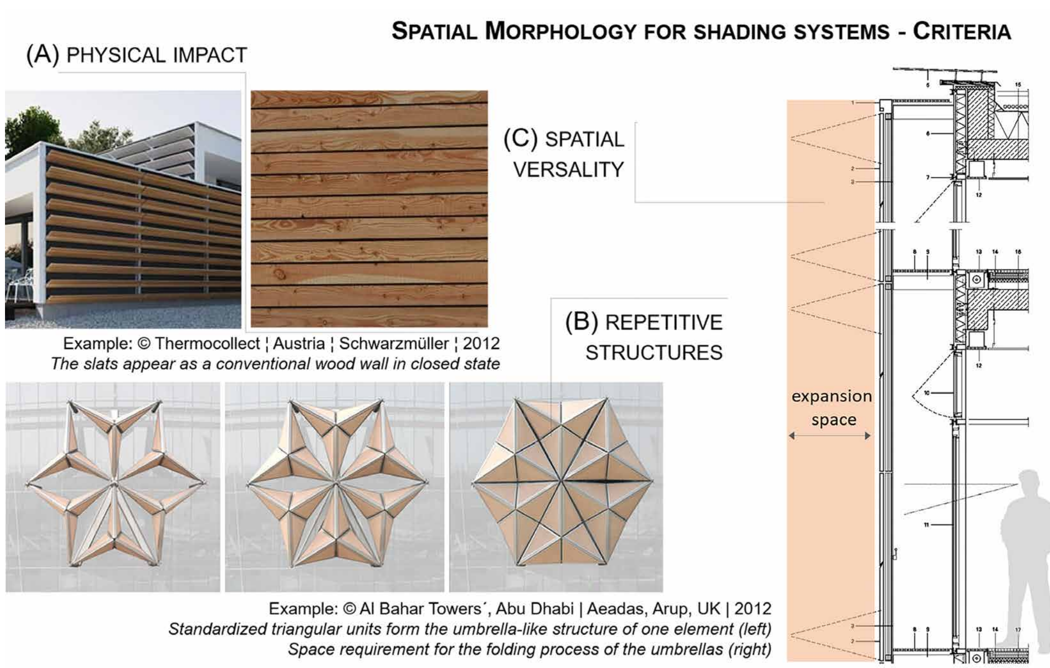


FIG. 1 Spatial morphology parameters for shading systems: (A) 'Physical Impact' deals with the visual kinetic patterns of the shading system in various adaptation states, (B) 'Repetitive structure' with the geometrical properties (size, scale, form of the element), and (C) 'Spatial Versality' with the mechanisms and need of space for motion. These parameters describe the geometrical design of the system *(Images retrieved from Thermocollect, pinterest.com).*

3.2 CATEGORISATION OF SHADING SYSTEMS

To make the geometrical characteristics of conventional shading systems visible, they are categorised according to their assembly types, orientation and motion, material properties, position relative to the façade, and the already mentioned spatial morphology criteria, as shown in Table 1. These parameters are considered to have a direct link to geometrical constraints, although there are other criteria that might indirectly influence the geometry (e.g. comfort requirements, climatic situation, economic constraints).

TYPES		FAÇADE ORIENTATION PREFERENCES	POSITION PREFERENCE	MATERIAL	MOTION	"SPATIAL MORPHOLOGY CRITERIA"		
						Physical impact	**Spatial versality**	**Repetitive structure**
Overhangs, fins, shelfs		South	exterior	all	fixed	static; planar, laminar appearance	horizontal expansion; space need is high	one unit
Brise-soleil, Louvres		East, west	exterior	all	fixed (with moveable or fixed slats)	semi-static; laminar appearance	horizontal; space need is medium to high	one element (repetitive)
Awnings		all	exterior	textile, aluminum, plastic	fixed, moveable	framed, homogenous, planar appearance	horizontal, sloped; space need is medium to high	one unit
Roller, shutters		all	exterior	steel, aluminum, plastics, glass	moveable	laminar, planar appearance	horizontal, vertical; space need is medium to high	one element (repetitive)
Venetian blinds		all	exterior, interstitial, interior	aluminum, metal, wood, glass, plastic, textile	moveable	laminar appearance	horizontal, vertical; space need is minimal	one element (repetitive)
Blinds, screens		all	exterior, interstitial, interior	aluminum, metal, wood, plastic, textile	moveable	planar, circular, polygonal appearance	vertical; space need is minimal	one element (repetitive)
Drapes, curtains, blackout screens		all	interior (seldom exterior)	textiles, plastic	moveable	Planar appearance	vertical; no space is need	one unit

TABLE 1 Categorization of conventional shading systems: Identified parameters that provide spatial information or influence on geometry

The constructive characteristics of shading systems are further classified by structural frame types (if not self-supporting), suspension systems (guide rails, hinges, brackets), and kinetic actuators (hydraulic, electric). Positioning relative to the building skin can be either external, internal, or interstitial, whereas the choice defines the spatial expansion bandwidth and performance efficiency. Besides being the best choice for thermal protection, external shading devices provide the most complex geometries and also higher structural and durability requirements, due to the exposure to climatic conditions and aesthetic visibility. Interstitial systems are less demanding in terms of spatial and structural requirements, but cause complicated maintenance requirements when they are moveable. For example, in closed-cavity façades, there is no maintenance option after being installed. Thus, the whole element must be exchanged in case of malfunction.

3.3 KINETIC PATTERNS

Folding, rolling, shifting, etc. are kinetic movements that require certain geometrical arrangements. Shading systems mainly use laminar (fold, flap) or planar (roll, shift) geometries to allow one- or two-dimensional motion. This approach limits the flexibility of shade vs. non-shade areas, and increases the conflict between shading and visual quality tasks. Either one or the other will not perform well, because the surface is shaded either too much or too little in relation to actual needs. Polygonal shapes, on the other hand, allow higher flexibility to cover precisely defined areas and allow the use of planar structures to enable a multi-directional motion (Fig. 2).

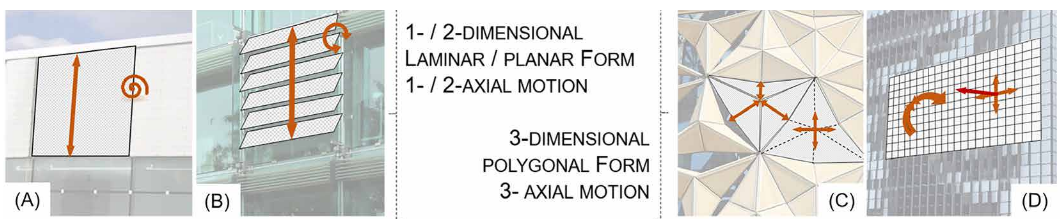


FIG. 2 Geometrical forms and motion types: Planar geometries (A) and laminar geometries (B) move generally in one or two dimensions, using a one- or two-axial mechanism. Three-axial mechanisms need more flexible forms, resulting in polygonal geometries (C) or, at least, rectangular geometries (D) allowing free motion towards three-axial mechanism. *(Images retrieved from flickr.com, pinterest.com, Wikipedia.com).*

This observation suggests that geometrical forms of shading systems seem to be directly related to motion-related criteria. The more flexible the form, the more flexible is the adaptation mechanism, and respectively, the motion pattern, and vice versa. The identified criteria of this observation are summarised in Table 2.

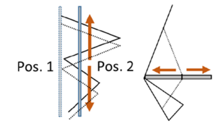
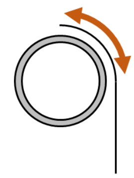
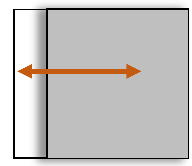
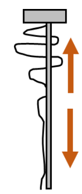
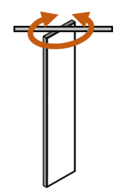
KINETIC MOTION TYPE		GEOMETRICAL FORM COVERAGE OF SPACE	DIRECTION OF MOTION	ADAPTATION SYSTEM	KINETIC MECHANISMS
Fold (e.g. blinds)		planar, laminar form polygonal form linear, grid coverage	2-dimensional 3-dimensional	guiding rails (in various positions), hinges, racks, racks with hydraulic actuator (into z-axis)	
Roll (e.g awnings)		planar form planar coverage	1-dimensional 3-dimensional	brackets, cords, reel	
Shift (e.g. screens)		planar, laminar form polygonal form planar, grid coverage	1-dimensional	guiding rails	
Wrap or lift (e.g. curtains)		planar (flexible) form planar coverage	1- to 2-dimensional	Guiding rails, cords, reel	
Flap (e.g. rotating screens)		planar, laminar form polygonal form linear, grid coverage	2-dimensional	Hinges or brackets, fixed in rails (rotation point)	

TABLE 2 Kinetic motions of shading systems: Selection of most applied motion types and their related criteria for adaptability and geometry

3.4 MOTION INTO THIRD DIMENSION

As mentioned, the complexity of the kinetic mechanisms increases with the complexity of the geometry of the components. The kinetic façade of the Al-Bahr Tower in Abu Dhabi (Attia, 2015) is a representative example of a complex, multi-directional folding mechanism. Inspired by the design of the Arabic mashrabiya, the architect developed origami-like shading "umbrellas" that fold radially via a linear actuator into the third dimension (like the opening of a blossom). Planar PTFE triangle units are steered by hydraulic actuators that "progressively open and close once per day in response to a pre-programmed sequence" (CTBUH, 2018). There are a few examples that use e.g. planar forms, such as the shifting panels of Tessellate™ by the initiative 'Adaptive Building Initiative' of the A. Zahner Company, or the lenses of the Arab World Institute in Paris by Jean Nouvel, to generate hexagonal geometries and patterns. Very few examples allow motion into the third dimension using rectangular geometries, such as e.g. the Wind veil façade project in Gateway Village by Ned

Kahn. Finally, newer solutions liberate themselves from geometrical and kinetic mechanisms and create a motion into the third dimension through their material-inherent properties, such as e.g. the biomimetic "materialsystem HygroScope" designed by Achim Menges and Steffen Reichert or the use of shape-memory alloys (SMAs). All of these examples (also shown in Fig. 3) have a more or less deep impact on the spatial morphology.

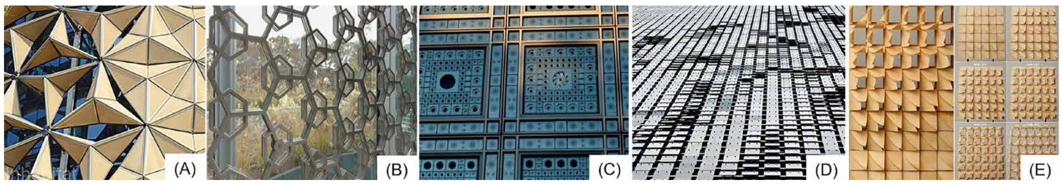


FIG. 3 Grid patterns and kinetic motion in complex systems: (A) hydraulic umbrella shades of Al Bahr Tower fold three-dimensional, (B) the Tesselate ™ concept shifts decorative metal sheets into changing grid patterns, (C) the Institut du Monde Arabe uses a complex photo lenses-like system, (D) the Wind veil façade of Ned Kahn allows wind to play with freely moving metal sheets, and (E) the adaptive biomimetic wood veneer HygroScope from Achim Menges and Steffen Reichert is able to bend automatically according to air humidity change. *(Images retrieved from flickr.com, pinterest.com, Wikipedia.com)*.

It might also be of interest to mention that some complex shading geometries are derived from local climatic conditions and related socio-cultural relations: Grid-like, repetitive patterns, such as the mashrabiya in the Islamic culture, are more frequent in regions with higher demands on privacy and higher solar radiation (subtropical, tropical, arid climate) than in cooler climatic zones. Grid-based forms also leave a constant shading pattern due to their frame structure - if it is not fully removeable. The adaptation degree is limited to the element within the grid. This will not be addressed in more detail in this paper. However, it is interesting that these patterns are based on geometrical formulae described by mathematical rules. These are seen as “universal law” in nature (cf. Stankov, 2018).

4 GROWTH GEOMETRIES IN NATURE

According to the works by Thompson (1945), “On Growth and Form”, and to more recent publications from Ball (2009), morphological and physiological adaptation has its causality in mathematical problem-solution. It is widely accepted that growth and form developing processes in nature use the laws of physics, whether inanimate or animate bodies. Nature deals with geometrical optimisation to allow growth at any time and any direction. Thus, applying mathematical analysis helps to understand patterns in nature (cp. Turing RD model) (Kondo & Miura, 2010) and might also support the understanding of adaptation mechanisms. It shall be noted that morphological processes in biology are strongly connected to chemical agents and triggers, and influences are difficult to describe solely with mathematical formulae (Morrison, 1987; Ball, 2009).

The basic geometrical form (starting from the molecular level) in biological morphologies is a grid-based shape, based on circular or polygonal units. Together with the basic form, certain growth patterns, such as spiral and sequential growth, allow the biological system to develop and adapt its form. Thus, to understand the adaptation mechanisms of biological organisms, the understanding of their basic geometrical form is necessary. In this section, examples of biological - seemingly static - growth patterns are presented to discuss their growth principles. Although these patterns are not directly associated with kinetic motion, they provide insights into the optimisation of surface geometries for (possible) multi-dimensional adaptability - the goal of kinetic systems.

The second part of this section then presents some kinetic mechanisms in nature and their possible relation to geometrical forms. It should be noted that geometrical forms, growth patterns, and kinetic mechanisms are not necessarily combined in one organism, but may be combined later in a technical solution.

4.1 UNIVERSAL LAW IN NATURE

Two general questions guide the search for biological role models in the context described above: Do geometrical forms play a role in adaptations of biological organisms? And, if so, how do geometrical forms support adaptability?

Shape is crucial for survival and adaptation to local conditions. A good example of this is the eco-geographical rules; these rules state that related species have developed different characteristics depending on the geographical region in order to adapt evolutionarily to the respective climatic conditions. This can affect the body volume (Bergmann's rule) or the relative size of the extremities (Allen's rule). Carl Bergmann suggested that the surface area to body volume ratio of animals correlates directly with the temperature of the region. Mammals and birds in cold regions are usually larger than in warm regions to efficiently maintain or to release body heat (Encyclopaedia Britannica, 2017). Large bodies have a smaller area to volume ratio. The Allen's rule, as a corollary rule to the Bergmann's rule, states that warm-blooded animals in colder regions have shorter protruding body parts relative to their body size than those in warmer regions for the same thermo-regulating reason (Encylopedia.com, 2018). Furthermore, animals living in regions of higher humidity have darker pigmentation than those living in drier regions, which is stated by the Gloger rule (Allaby, 2018). These rules are found in any evolutionary adapted animal, as well as in plants. Although these examples are not dynamic in the sense of the paper, it can be assumed that certain geometrical forms and evolutionary growth patterns also support dynamic adjustments. In the search for these principles, especially in plants (which are unable to move and need to adapt to various local changes and impacts), it has become apparent that particularly geometrical patterns of surfaces facilitate dynamic adaptation. Thus, the analogy search is divided into the investigation of basic geometrical forms (basic growth patterns) and dynamic adaptation mechanisms (kinetic mechanisms).

4.2 BASIC GROWTH PATTERNS IN NATURE

Surface structures and their subsystems are decisively responsible for the control of environmental impact. Their biological patterns, applying geometrical principles such as the Golden Ratio, platonic bodies, and sequential growth, allow differentiated and adaptable morphologies. Figures of pentagonal symmetry and with a high repetitive pattern, in particular, are closely linked to growth. For example, the geometrical arrangements of seeds, branches, leaves or petals using the Golden Ratio allow not only optimisation of the surface area to the solar exposure, as shown in the sunflowers (Fig. 4, A), but also enable kinetic (folding) mechanisms, as shown by the fern leaf (Fig. 4, D).

The Golden Ratio defines herein the geometrical basis for the ability to change, which is enabled by growth patterns such as the Fibonacci sequence. The mathematical connection between the Golden Ratio and the Fibonacci sequence is shown in the Golden Spiral, a proportional growth of φ in a rectangular pentagon (see (C) in Fig. 4), which appears in the static structure of the sunflower blossom and also in the dynamic rolling function of the fern leaf. At first glance, the sunflower does not appear to be a suitable role model for the investigation, since the surface of the sunflower is static and oriented towards maximum solar radiation harvesting in a confined space - an opposite intention to the goal of shading systems. The basic geometrical form, however, allows spatial expansion; the individual seeds of the flower could be multiplied into three-dimensionality within the condensed area due to their polygonal structure. This polygonal surface also corresponds well to the promising examples of complex kinetic shading systems. The aim could be to enlarge the shading surface without consuming more façade surface area – voronoi, tessellation, tangram geometries, and origami patterns could serve as a possible mathematical transfer path. In addition, these geometries allow multi-directional motion, as the fern leaf shows (Fig. 4, D). Shading systems would have more flexibility for individual shading of the surface if this approach were used instead of the conventional one.

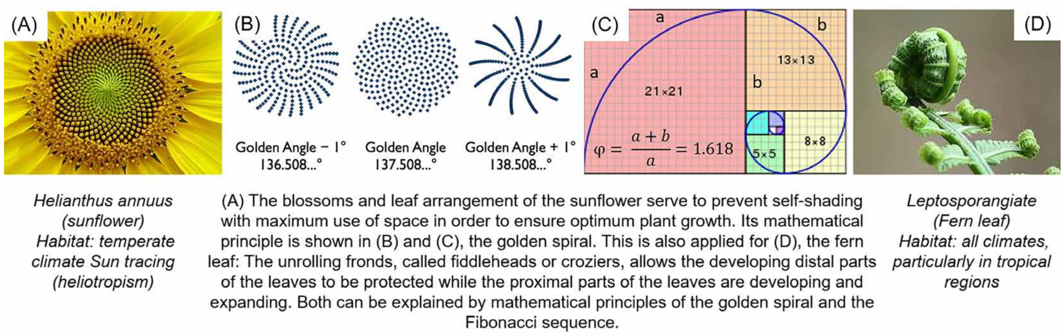
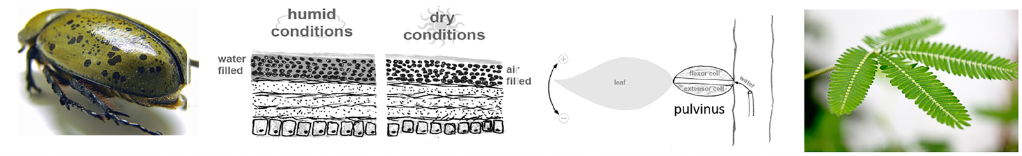


FIG. 4 Biological role models to demonstrate geometrical forms for the optimisation of surfaces and for growth patterns *(Images retrieved from www.greatmathsteachingideas.com, pinterest.com, Wikipedia.com).*

4.3 KINETIC MECHANISMS IN NATURE

The screening of the biological database of the BioSkin project (Gosztonyi, Gruber, Judex, Brychta, & Richter, 2013) revealed that dynamic adaptation and geometrical form optimisation are not always to be found in one role model. For example, adaptive biological organisms that cannot move change their properties ‘passively’ through inherent structure-material characteristics. These can respond dynamically to environmental changes by changing their properties or effects to the environment, e.g. by structural colours, photonic crystals. One example of this kind of adaptation is the *Dynastes beetle* (see left in Fig. 5). Other ‘active’ adaptations are achieved by kinetic mechanism activated through physiological or biophysical processes, such as e.g. folding or curling processes initiated by the Turgor pressure, as applied in the *Mimosa Pudica* (see right in Fig. 5). Kinetic mechanisms are not necessarily related to geometry but influence its morphology. Folding or rolling mechanisms seem to be the most commonly applied adaptation mechanism for shading systems. This also applies for biological role models – insofar as they have been investigated in this work. However, a refined approach must be applied by using detailed abstractions of the search questions and by combining role model functions.



Dynastes Hercules beetle
Habitat: tropical
Structural colour change

Photonic crystal effect is based on the composite of air-filled (n=1 = green) and water-filled (n=1.33 = black) cuticle. Sun light refracts at the chitin-air-interfaces and will be scattered so that the beetle appears differently according to the refraction properties. (S. Gosztonyi, S. Richter: BioSkin)

The pulvinar movement is caused by changes in turgor or hydro-static pressure that leads to contraction or expansion of the leaf tissue. The pulvinus is located at the base of each leaflet. (S. Gosztonyi, S. Richter: BioSkin)

Mimosa Pudica
Habitat: tropical, temperate
Dynamic actuator /osmosis

FIG. 5 Adaptation mechanisms in nature: Dynastes beetle (left) presents a static adaptation by photonic crystals that change its colour according to a changing humidity level. The Mimosa Pudica (right) adapts fast if contact occurs due to the Turgor pressure, an osmotic flow of water through cells *(Images retrieved from Wikipedia. Sketches: S. Gosztonyi, & S. Richter).*

5 CONCLUSION

To answer question one, regarding the role of geometrical patterns in shading systems. Geometrical patterns do not play a major role in conventional shading systems; it seems that the goal of covering the façade area with simple or maximum area-covering forms is of utmost importance. More complex geometrical forms, such as circular or polygonal geometries, are found in vernacular shading systems and have become more popular today due to the digitalisation in design and production. It is assumed that a further development of the polygonal geometries for shading systems could lead to a better interaction between visual comfort and shading function, because the shaded area can be more specifically defined. A follow-up study to this assumption is currently in development.

The second question, about the influence of spatial morphology criteria and geometrical form on the flexibility of adaptation, has not yet been fully answered. Some technical solutions have been studied and it has been proven that more complex geometrical forms are more closely related to a higher flexibility of kinetic motion. In polygonal forms, the kinetic mechanism allows any movement into the third dimension, but simple kinetic mechanisms, such as folding and rolling mechanisms, also allow this expansion. The investigation of biological role models and their adaptation mechanisms supports the hypothesis that polygonal surface geometries (whether at micro or macro level) are the basis for flexible dynamic motions. These geometries enable the multidirectional 'growth' of a system. A possible transfer link between biological principles and a technical solution could be the application of mathematical models, such as the voronoi, tessellation, tangram geometries, and origami patterns. The adaptation patterns in nature have so far only been touched upon and will be a core topic for further studies in order to search for further answers to the second question.

5.1 NEXT STEPS

The purpose of future studies is to continue the above-mentioned investigations and to develop prototypes using certain mathematical models in order to create multi-directional kinetic shading systems that do not use more space but shade more flexibly. Furthermore, the assumption will examined that the visual quality and shading efficiency improve equally if the shaded area of a façade is defined by a grid.

Acknowledgements
The paper is based on earlier work of the author on biomimetic potentials for energy efficiency of façades and the development of design criteria for adaptive façades in a Short-Term Scientific Mission of the COST TU1403 "Adaptive Façade Network". The categorisation of dynamic shading systems was created on the basis of the database of the Working Group 1 in COST TU1403. The author would therefore like to thank the members of the COST TU1403 for the information and framework conditions to carry out this work, as well as the TU Delft Architectural Façades and Products Research Group (AF&P) for the valuable discussions, which were beneficial to the general work related to this topic.

References
Aelenei, D., Aelenei, L., & Vieira, C. P. (2016). Adaptive Façade: concept, applications, research questions . *Energy Procedia 91*, pp.269-275.

Allaby, M. (2018). *Gloger's rule*. Retrieved from Oxford Reference - A Dictionary of Zoology. Retrieved from http://www.oxfordreference.com/view/10.1093/acref/9780199233410.001.0001/acref-9780199233410-e-3667

Al-Obaidi, K. M., Ismail, M. A., Hussein, H., & Abdul, A. M. (2017). Biomimetic building skins: An adaptive approach. *J. Renew. Sustain. Energy Review 79*, pp.1472-1491.

Attia, S. (2015). Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. *Adv Build Skins (Economic Forum, 2015)*, pp.1254 - 1262. doi:10.5339/connect.2017.qgbc.6

Ball, P. (2009). *shapes. Nature's Patterns. A tapestry in Three Parts*. Oxford: Oxford University Press.

Barozzi, M., Lienhard, J., Zanelli, A., & Monticelli, C. (2016). The sustainability of adaptive envelopes: developments of kinetic architecture. *Procedia Engineering 155*, pp.275-284.

Cohen, Y., Reich, Y., & Greenberg, S. (2014). Biomimetics: Structure - Function - Patterns Approach. *J Mech Des 136 (1)*, 111108. doi:10.1115/1.4028169

COST TU1403. (2014-2018). *COST TU1403 – Adaptive Facades Network*. Retrieved 05 28, 2018, from COST TU1403 Adaptive Facades Network: http://tu1403.eu

CTBUH. (2018, 04 07). *Al Bahar Towers - External Automated Shading Systems*. CTBUH Innovation Award 2012. Retrieved from Council on Tall Buildings and Urban Habitat Annual Award. Retrieved from http://www.skyscrapercenter.com/building/id/9129

Encyclopaedia Britannica. (2017, 05 16). *Bergmann's Rule*. Retrieved from Encyclopaedia Britannica. Retrieved from https://www.britannica.com/science/Bergmanns-Rule

Encylopedia.com. (2018, 04 16). *Allen's rule (originally published by Oxford University Press 2004)*. Retrieved from Encylopedia.com - A Dictionary of Ecology. Retrieved from https://www.encyclopedia.com/earth-and-environment/ecology-and-environmentalism/environmental-studies/allens-rule

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *J. Renew. Sustain. Energy Review 55*, pp.863-884.

Gosztonyi, S. (2015). Adaptive Façade – which criteria are needed? *facade 2015 - Computational Optimisation (Proceedings, HS OWL, Detmold)*, pp.84 - 95.

Gosztonyi, S., Gruber, P., Judex, F., Brychta, M., & Richter, S. (2013). *BioSkin - Research potentials for biologically inspired energy efficient façade components and systems*. Vienna: nachhaltig wirtschaften BMVIT.

Hutchins, M. (2015). *High performance dynamic shading solutions for energy efficiency and comfort in buildings*. Executive summary. Abingdon, UK: ES-SO.

Kondo, S., & Miura, T. (2010). Reaction-Diffusion Model as a Framework for Understanding Biological Pattern Formation. Review. *Science 329 (5999)*, pp.1616-1620. doi:10.1126/science.1179047

Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., & Knippers, J. (2011). Flectofin: a hingeless flapping mechanism inspired by nature. *Bioinsp. Biomim. 6*, 045001.

Loonen, R., Trcka, M., Costola, D., & Hensen, J. (2013). Climate adaptive building shells: State-of-the-art. *Renewable and Sustainable Energy Reviews*, pp.483-493.

Menges, A. (2012). Biomimetic design processes in architecture: morphogenetic and evolutionary computational design. *Bioinspir. Biomim. 7*, 015003.

Morrison, P. (1987). Reviewed Work: On Growth and Form: Fractal and Non-Fractal Patterns in Physics, edited by H. Eugene Stanley and Nicole Ostrowsky. *Scientific American 256 (1)*, 26-27. Retrieved from http://www.jstor.org/stable/24979292

Pesenti, M., Masera, G., Fiorito, F., & Sauchelli, M. (2015). Kinetic Solar Skin: A Responsive Folding Technique. *Energy Procedia 70*,pp. 661 - 672.

Sartori, J., Pal, U., & Chakrabarti, A. (2010). A methodology for supporting "transfer" in biomimetic design. *Artif. Intell. Eng. Des. Anal. Manuf. 24 (4)*, 483-505. doi:10.1017/S0890060410000351

Stankov, G. (2018, 02 12). *The Universal Law of Nature*. Retrieved from Stankov's universal law press: http://www.stankovuniversallaw.com/the-universal-law-of-nature/

Thompson, D. (1945). *On Growth and Form*. Cambridge University Press: NY.

Werner, S. (2016). European space cooling demands. *Energy (110)*, pp.148 - 156.

Towards New Metrics for the Characterisation of the Dynamic Performance of Adaptive Façade Systems

Lorenza Bianco[1,2,†], Ylenia Cascone[1], Stefano Avesani[3], Pascal Vullo[3], Timea Bejat[2], Roel Loonen[4], Stefan Koenders[4], Francesco Goia[5], Valentina Serra[1], Fabio Favoino[1*]

* corresponding author
1 Politecnico di Torino, Department of Energy, Torino, Italy, fabio.favoino@polito.it
2 Univ Grenoble Alpes, CEA, LITEN, DTS, SBST/LCEB, INES, Grenoble, France
3 Institute for Renewable Energy. Eurac Research, Bolzano, Italy
4 Eindhoven University of Technology, the Netherlands
5 Department of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology, NTNU, Trondheim, Norway

† This paper is dedicated to the memory of Dr. Lorenza Bianco, a bright and inspiring colleague who recently passed away.

Abstract

Traditional façade characterisation metrics such as U-value and g-value are of limited value in the design process of buildings with adaptive façades. This issue is particularly important for adaptive façade components that have the capability of controlling thermal energy storage in the construction thermal mass. Building performance simulations can help to analyse the performance of buildings with adaptive façades, but such studies usually only provide information about the energy and comfort performance at room level. Consequently, there is a need for development and testing of new façade-level performance metrics that can be used to compare the performance of different adaptive façade components. This paper presents experiences and lessons learned from four European R&D projects that have introduced novel metrics to capture the dynamic performance of adaptive opaque façades. Characteristics of the different metrics are described, and their similarities and differences are compared and contrasted. The paper highlights the main benefits of metrics that can capture dynamic effects, and concludes by providing directions for future work.

Keywords

adaptive façade, double skin, adaptive insulation, performance metrics, experimental characterisation

DOI 10.7480/jfde.2018.3.2564

1 INTRODUCTION

Adaptive façades have the ability to adjust their configuration or physical properties in response to changes in interior and exterior boundary conditions. When this adaptation is controlled in an effective way, such façades offer a remarkable potential for comfort improvements and energy savings (Loonen, Trčka, Cóstola, & Hensen, 2013). Typical examples of adaptive façades include switchable windows (Favoino, Overend, & Jin, 2015), dynamic insulation (Jin, Favoino, & Overend, 2017) (Favoino, Jin & Overend, 2017) and movable exterior shading screens (Fiorito et al., 2016).

During the design phase of buildings with adaptive façades, there is a need for quantitative information about the performance of such systems (Loonen, Singaravel, Trčka, Cóstola, & Hensen, 2014). This information can support the decision-making process and the comparison with alternative advanced and traditional façade systems. One way to obtain this information is with the help of building performance simulations. In this way, performance can be expressed in terms of indicators that are of direct interest to the relevant stakeholders (e.g. life-cycle costs or comfort exceedance hours), while accounting for dynamic operational strategies of the adaptive façade (Loonen, Favoino, Hensen, & Overend, 2017). It must be realised, however, that such simulations require detailed inputs about the characteristics of the building, the façade system, and the way it will be used. This type of information is generally not available in the earlier design stages. Moreover, the availability of component models for innovative adaptive façade systems tends to be scarce, while a high level of user expertise is required to get meaningful simulation results. As a consequence, there is a need for simpler methods and metrics to characterise the performance of adaptive façade components.

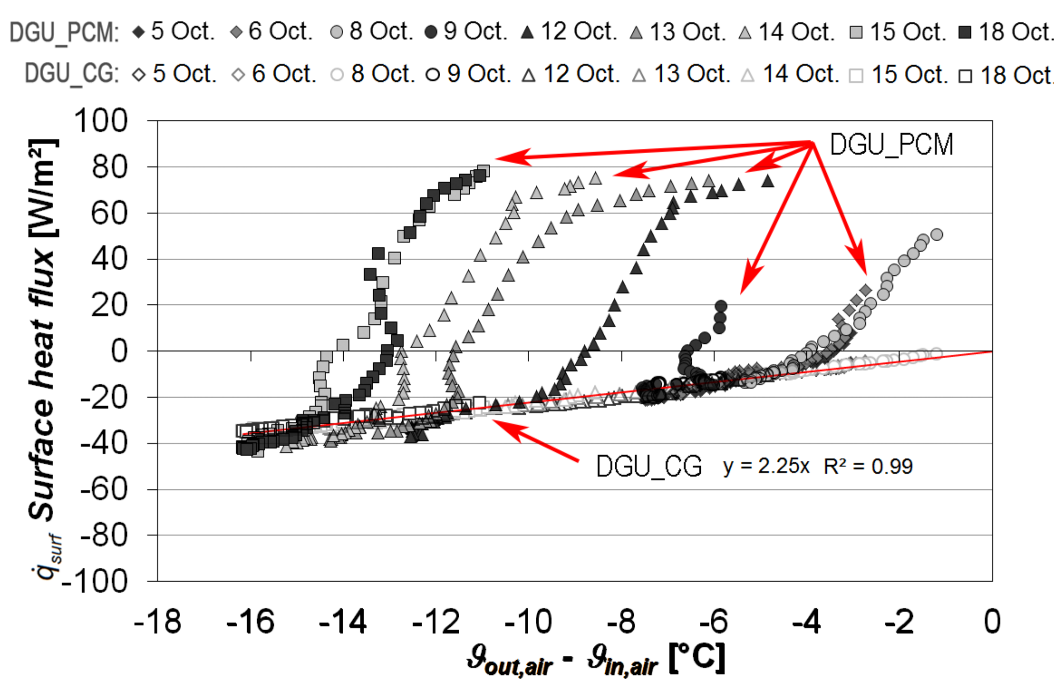


FIG. 1 Linear regression analysis to identify the U-value in a conventional and in a PCM glazing unit *(Goia et al. 2014)*

Recent research has highlighted how conventional performance metrics, such as the U-value, cannot be used to describe the performance of adaptive systems, as the thermophysical behaviour is too far from the assumptions under which this metric can be measured or calculated. This fact can be seen in Fig. 1, where a comparison between conventional glazing and PCM glazing is shown, as far as the assessment of the in-situ U-value (Goia Perino, & Serra, 2014) is concerned. The graphs in Fig. 1 represent the relationship between the indoor – outdoor temperature difference ($\varrho_{out,air}$ - $\varrho_{out,in}$) and the heat flux through the glazed component, for the glazing with an air cavity (traditional double glazing unit with clear glass, DGU_CG) and for the PCM filled glazing (DGU_PCM). While a conventional glazing unit (DGU_CG) can be characterised in terms of U-value, which is quantified by the slope of the linear regression line (y=2.25x, thus U-value = 2.25 W/m^2K), the inertial effect in PCM glazing (DGU_PCM) prevents the assessment of a U-value being carried out, as it is impossible to identify a linear relationship between temperature difference and heat flux through the glazing (U-value).

Other studies have highlighted the importance of performance metrics for capturing the performance of transparent ventilated façades. Di Maio and Van Paassen (2001) used, for the first time, the concept of pre-heating efficiency (η_{PH}) for transparent double skin façades using the air cavity to pre-heat the supply ventilation air. Corgnati, Perino, and Serra (2007) developed these concepts further, adopting the dynamic insulation efficiency (ε) for transparent double skin façades, using the cavity air to remove solar loads transmitted through the glazing (outdoor air curtain ventilation strategy). The common characteristics of these metrics are:

- both are developed to measure the additional amount of solar radiation either added or removed by means of the ventilation mechanisms of the façade or room behind it;
- they are normalised with respect to the boundary conditions (temperatures, amount of solar radiation, solar geometry etc.), so that they are, to a large extent, independent from them;
- they are based on hourly or daily data, which are averaged over a longer period;
- they are not derived from physical parameters (based on a physical model), but are derived from time series of data (experimental or simulated), of the order of months or years.
- the thermal storage mechanisms and thermal mass is not accounted for, and these metrics are therefore applicable only to light-weight façade components (typically transparent façades).

2 METHODOLOGY

This paper presents experiences and lessons learned from four adaptive façade R&D projects carried out at different institutes across Europe, with particular emphasis on the identification and application of new performance metrics for adaptive façades. The following four R&D projects are presented: (i) the ACTive, RESponsive and Solar façade module (ACTRESS) at Politecnico di Torino; (ii) the SMARTglass project at Politecnico di Torino; (iii) the ADAPTIWALL multi-functional lightweight façade panel at INES CEA and EURAC, and (iv) the Active Insulation Project at TU Eindhoven.

In particular, the paper first presents specific performance metrics devised into the four different adaptive façade projects. This is organised into four different sections (one per project) in which a first description of the adaptive façade system is given, the definitions and characteristics of all metrics are provided, together with the quantification of the specific metric for the related adaptive façade system. Finally, similarities and differences between the different metrics are contrasted, identifying their main benefits, the specific adaptive technology they refer to, and how they can capture the dynamic effect of the adaptive system. The paper concludes by providing directions for future work.

3 PERFORMANCE METRICS FOR THE ACTRESS PROJECT

The ACTRESS (ACTive RESponsible and Solar) Multifunctional Façade Module (MFM) was developed in the context of an Italian national research project (PRIN) between 2008 and 2010. It is made of two different sub-systems: an Opaque Sub-Module (OSM) and a Transparent Sub-Module (TSM). For the purposes of this paper, only the OSM is discussed (as the TSM metrics are not relevant for this paper). A comprehensive description of the MFM and of its performance can be found in Favoino, Goia, Perino, and Serra (2013) and (2016). The OSM (Fig. 2) is made up of the following (from outside to inside):

- an external skin is formed by an amorphous silicon PV panel (aSi PV, η pv = 6%, g-value pv = 0.27);
- 120mm ventilated air cavity (floor to floor height) which can be operated in either thermal buffer, supply air, outdoor air curtain and exhaust air modes (with natural, hybrid and mechanical ventilation) according to the boundary conditions.
- an opaque sandwich wall composed of: a double VIP (Vacuum Insulation Panel) layer (R=10 m^2K/W); two layers of Phase Change Materials (PCMs) directly facing the indoor environment with melting temperatures of 27 °C and 23 °C, respectively; an electric heated foil directly powered by the aSi PV panels, in between the two PCM layers, thus allowing for active thermal energy storage (activation of the PCM on-on-demand); an internal and external gypsum board (one facing the ventilated cavity and one the internal environment). This system is effectively a solar LHTES (Latent Heat Thermal Energy Storage System).

The design of the OSM aimed to minimise the heat losses and gains (by conduction and ventilation) by means of the opaque cavity ventilation and the VIP panels, and by storing the solar energy directly into the PCM layers to be supplied to the indoor environment when needed.

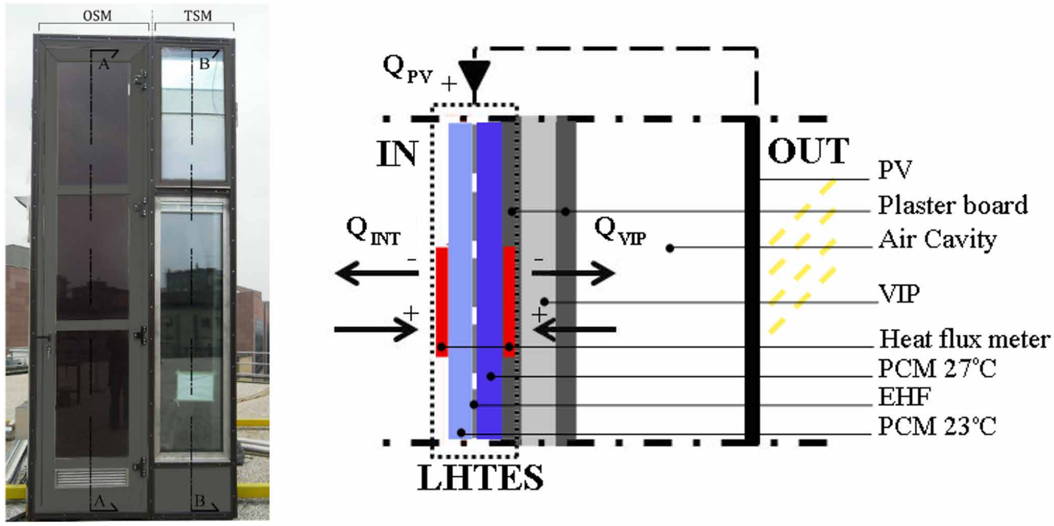


FIG. 2 Front view of the ACTRESS prototype (left) and cross sections and energy balance of the Solar LHTES (right)

To characterise the performance of this ventilated solar LHTES, alongside with the measured U-value of the system (of 0.1 W/m^2K[1], in line with the calculation from physical parameters of the VIP, gypsum, and PCM layers), different performance metrics were used. These are presented in the following sections: 3.1.1 and 3.1.2, which are adapted from the above mentioned metrics for transparent façades, and 3.1.3 and 3.2.1 to .3, which are newly developed.

3.1 PERFORMANCE METRICS FOR THE VENTILATED CAVITY

3.1.1 Dynamic insulation efficiency – ε [-]

Dynamic insulation efficiency (ε [-], Corgnati et al., 2007) ε is defined as the capability of the opaque module to reduce the entering heat fluxes (due to temperature differential and solar radiation) by means of the façade ventilation (between 0 and 1), when operating in Outdoor Air Curtain (OAC) mode, i.e. mainly in mid-season and summer. According to the boundary conditions of the system considered, it can be defined for the Opaque Ventilated Cavity only (OVF) or for the whole OSM (including the PCM). For the specific case (Fig. 3), with the low G-value of the PV layer, the summer mechanical ventilation and the use of the PCM, the OSM is, on average (50% cumulative frequency), adiabatic (completely eliminating the heat gains or reversing them, when ε > 1).

$$\varepsilon = \frac{\dot{Q}_{vent}}{\dot{Q}_{out}} \text{ [-]}$$

Equation 1

1 The measured U-value resulted from a long-term measurement (Favoino et al. 2013).

3.1.2 Pre-heating efficiency – η_{PH} [-]

Pre-heating efficiency (η_{PH} *[-]*, DiMaio & Van Paassen, 2001) represents the ratio between the quantity of energy (enthalpy) in the air that flows inside the façade and the energy (enthalpy) necessary to pre-heat the ventilation air (it has a value between 0 and 1). In the specific case (Fig. 4), during the day (solar radiation I higher than 1), the heat losses through the air supplied to the indoor space are halved (approx. 0.50) on average (50% cumulative frequency); when also considering night-time operation, these heat losses are reduced only by 20%.

$$\eta_{PH} = \frac{T_{exh} - T_{inlet}}{T_{out} - T_{in}} \quad [-]$$

Equation 2

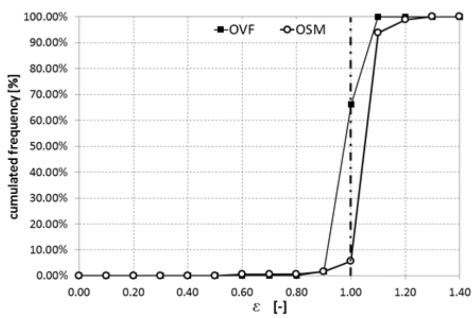


FIG. 3 Dynamic insulation efficiency of the OSM *(Favoino et al. 2016)*

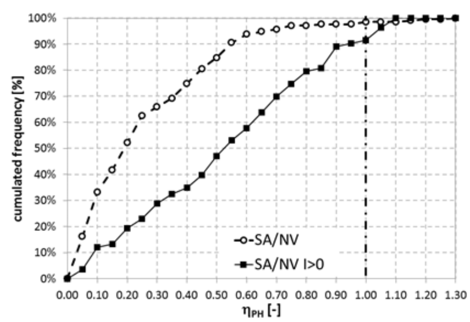


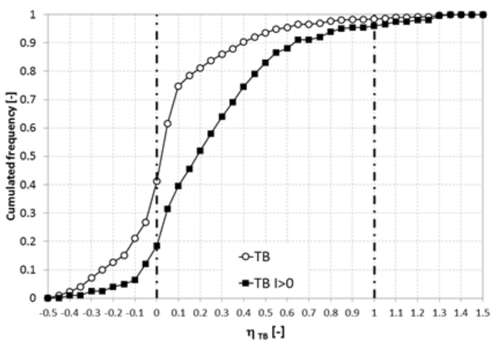
FIG. 4 Preheating efficiency of the OSM *(Favoino et al. 2016)*

3.1.3 Thermal buffer efficiency – η_{TB} *[-]*

Thermal buffer efficiency (η_{TB} *[-])* is a novel parameter (Favoino et al., 2013) similar to the so-called adjustment factor b_{tr} defined in the ISO 13789:2007 Standard (EN ISO, 2007), used when operating in Thermal Buffer (TB) mode, defining a reduction factor (from -1 to 1) for the heat losses due to increased temperature of the cavity. In the specific case (Fig. 5), when adopting a thermal buffer strategy, the heat losses by conduction of the OSM can be reduced, on average (50% cumulated frequency) by 25% during the day (I higher than 1), or by only 5% when night-time operations are also considered. Negative values represent higher heat losses, due to radiation, to the night-sky during winter.

$$\eta_{TB} = \frac{T_{out} - T_{cav}}{T_{out} - T_{in}} \quad [-]$$

Equation 3



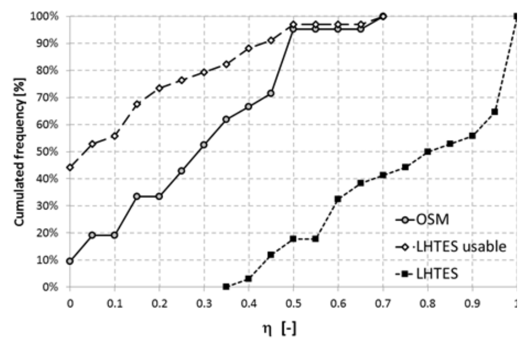


FIG. 5 Thermal buffer efficiency of the OSM *(Favoino et al. 2016)*

FIG. 6 Efficiency of the LHTES *(Favoino et al. 2016)*

As far as the LHTES (e.g. PCM layers) is concerned, the analysis was carried out by analysing the energies accumulated/transmitted through the opaque sub module, by means of a first principle analysis of the daily energies exchanged across the solar LHTES system (Q_{PV}, Q_{IN} and Q_{VIP}, as defined in Fig. 2). Due to the dynamics of the solar LHTES, particular attention should be paid to the starting time of the daily first principle analysis. Moreover, these are not calculated as hourly or sub-hourly values, but as daily values, therefore longer duration testing is needed to elaborate on results in metrics that are independent from outdoor boundary conditions.

3.2 PERFORMANCE METRICS FOR THE LATENT HEAT THERMAL ENERGY STORAGE SYSTEM

3.2.1 Utilisation factor of the solar LHTES system– η_{LHTES}

Utilisation factor of the solar LHTES system (η_{LHTES} *[-])* is defined as the ratio between the energy stored in the PCM layer and the solar energy converted by the PV panels, over a daily period. It gives straightforward information about the fraction of converted thermal energy that is stored in the latent energy buffer, but it does not provide any information about the fraction of the converted energy that is actually used as a positive contribution to the room heating. In fact, only part of the heat is released towards the indoor environment after it is stored in the PCM or directly, while the remaining part is lost towards the ventilated air cavity of the OSM. The η_{LHTES} (value between 0 and 1) measures the efficiency of storing solar converted electrical energy into the specific latent heat thermal energy storage system, independently of its position or integration in the building.

$$\eta_{LHTES} = \frac{\int_{6am}^{6\,am+1} \dot{Q}^{+}_{LHTES} \cdot d\tau}{\int_{6\,am}^{6\,am+1} \dot{Q}_{PV} \cdot d\tau}\ [\text{-}]$$

Equation 4

3.2.2 Utilisation factor of the usable energy of the LHTES– $\eta_{\text{LHTES-Usable}}$ [-]

Utilisation factor of the usable energy of the LHTES ($\eta_{\text{LHTES-Usable}}$ [-]) is defined by the ratio between the energy delivered towards the indoor environment by the LHTES during its discharge phase and the energy stored in the LHTES over a daily period (ini and end subscripts indicate the start and the end of the discharge phase of the PCM in the LHTES). This efficiency describes the amount of energy that can be delivered to the indoor environment in order to reduce space heating compared to the total energy stored in the LHTES. The complementary part of this energy that which is lost from the LHTES. The $\eta_{\text{LHTES-usable}}$ measures the efficiency of integrating the latent heat storage into the building envelope, and specifically into the OSM of the ACTRESS MFM.

$$\eta_{\text{LHTES-usable}} = \frac{\int_{ini}^{end} \dot{Q}_{LHTES}^{-} \cdot d\tau}{\int_{6AM}^{6\,AM+1} \dot{Q}_{LHTES}^{+} \cdot d\tau} \quad [-]$$

Equation 5

3.2.3 Utilisation factor of the OSM system– η_{OSM} [-]

Utilisation factor of the OSM system(η_{OSM} [-]) is defined as the ratio between the thermal energy released by the LHTES towards the indoor environment over a single day, and the PV-converted energy, over the same time interval. It measures the efficiency of delivering the solar converted electric energy towards the indoor environment, after being stored in the designed latent heat thermal energy storage integrated into the building envelope, for space heating purposes. This efficiency is higher than $\eta_{\text{LHTES-Usable}}$ as, in addition to the energy converted by the PV, it also includes the thermal energy flowing to the LHTES from the air cavity. Meanwhile, the difference between h_{LHTES} and h_{OSM} gives a measure of the energy dissipated by the LHTES towards the air cavity.

$$\eta_{\text{OSM}} = \frac{\int_{6\text{am}}^{6\text{ am}+1} \dot{Q}_{\text{INT}}^{-} \cdot d\tau}{\int_{6\text{ am}}^{6\text{ am}+1} \dot{Q}_{\text{PV}} \cdot d\tau} \quad [-]$$

Equation 6

In the specific case (Fig. 6), on average (50% of cumulated frequency), on a daily basis, about 80% of the solar energy converted by the PV is stored in the latent heat storage (η_{LHTES}), but only 30% is delivered to the indoor environment, as most of the converted solar energy is lost to the air cavity (despite the presence of the VIP insulation). This is due to the much higher temperature differential towards the LHTES and the cavity, as compared to that between the LHTES and the indoor environment.

The results show that the performance on the OSM cannot be described only by standardised metrics such as the U-value. In fact, the specific measured U-value corresponds to the calculated one, although the heat losses and gains through conduction and convection could be much less than the calculated ones by means of U-value, due to the different operating modes of the system. In addition to these performance metrics, metrics that consider the daily total energy balance of the façade system are also considered, although, for brevity, these are not presented here for the ACTRESS project, but will be discussed in the context of the following projects.

4 PERFORMANCE METRICS IN THE SMARTGLASS PROJECT

The SMARTglass project, funded by Regione Piemonte in 2010 (Goia et al. 2014), was part of the activities of the Cost Action 1403 Adaptive Façades Network. The experimental campaigns, which were carried out in two phases at the TWINS outdoor test facility in Politecnico di Torino, Italy, involved the following technologies (Fig. 7):

- DGU: a reference double glazing unit (clear glass panes) with air;
- DGU_PCM: a double glazed unit (clear glass panes) with cavity filled with PCM (paraffin wax)
- TGU : a reference low-e triple glazing unit with 90% argon;
- TGU_TT : the TGU with an adjacent thermotropic layer (switch in the optical properties in the range 28 °C to 34 °C (Bianco, Goia, Serra, & Zinzi, 2015)) on the outer side;
- TGU_TT+PCM(IN): the TGU with an adjacent thermotropic layer on the outer side and its inner cavity filled with PCM (paraffin wax with a melting temperature range between 33 °C and 37 °C);
- TGU_TT+PCM(OUT): the TGU with an adjacent thermotropic layer on the outer side and its outer cavity filled with the PCM.

A comprehensive description of the experimental test rig, materials, technologies and their performance during the different phases was presented in Goia et al., (2014) (Phase 1) and Bianco, Cascone, Goia, Perino, and Serra (2017a) and (2017b) (Phase 2).

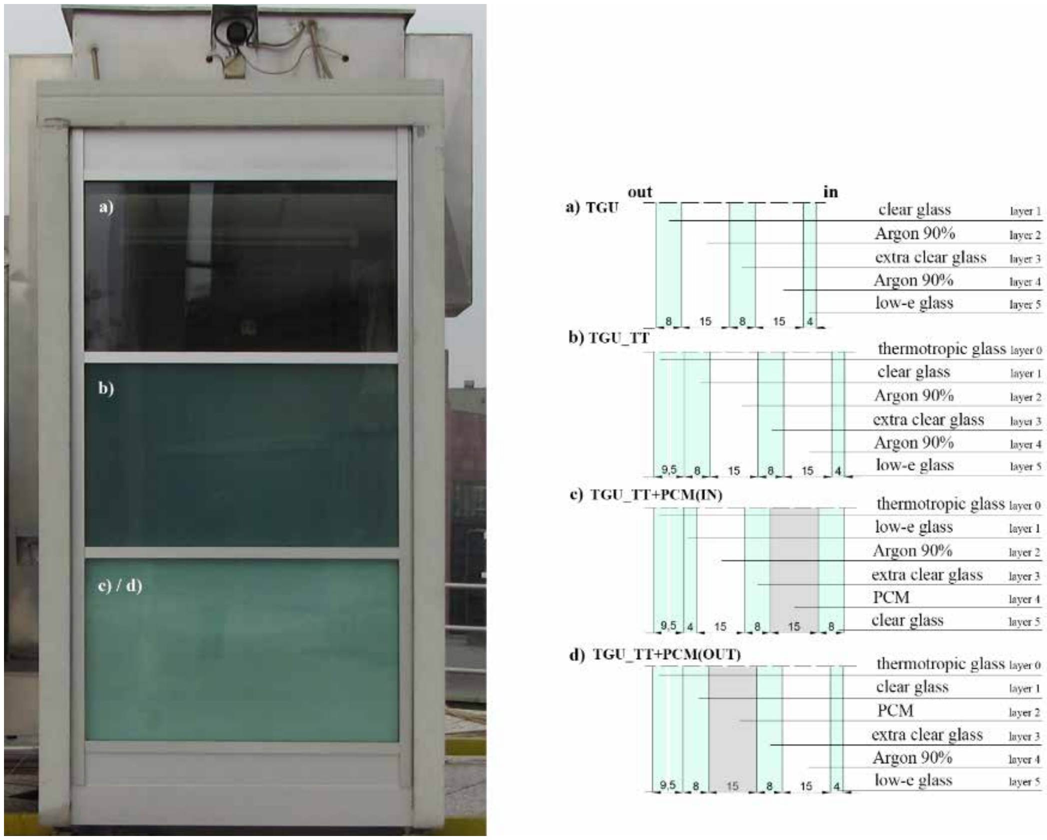


FIG. 7 Test cell and scheme of the SMARTglass technologies (Phase 2: *Bianco et al., 2017b*)

Compared to standard glazing, a PCM-based glazed unit (either double or triple pane unit) seeks to ameliorate the indoor surface temperature's fluctuation and reduce energy gains and losses. Through the interaction with the incident solar radiation, the PCM layer in these systems acts as a storage medium and as a solar shading device. When combined with a thermotropic layer (TGU_TT+PCM), a higher degree of control over the system is intended, as the thermotropic layer acts as a switchable shading system capable of regulating the phase change of the PCM.

In order to characterise the performance of these technologies, alongside the analysis of the hourly profiles of various physical properties (outdoor surface temperature, heat flux, transmitted solar irradiance, solar transmittance and visible transmittance), an equivalent solar factor was also evaluated from the in-situ measurements, calculated from daily measurement.

A full description of the methodology to evaluate the G-value on a daily basis from non-calorimetric measurement is given in Goia and Serra, (2018). The measurement of the equivalent G-value adopted an innovative measurement method enabling estimates of this metric based on the daily energy balance of the façade (Favoino et al., 2016; Bianco et al., 2017a), although a low accuracy of this measurement was achieved in this case mainly due to the variation in diurnal behaviour of the PCM-filled glazing systems, due to the strong influence of varying boundary conditions (temperatures and solar radiation) (Bianco et al. 2017a).

Total daily energies and long-term total energies (for a certain number of consecutive days for each season) were additionally analysed.

4.1 FAÇADE ENERGY BALANCE PERFORMANCE METRICS

4.1.1 Total daily energy – E24,tot [Wh/m2]

Total daily energy ($E_{24,tot}$ [Wh/m²], Bianco et al., 2017a; Goia et al., 2014) is defined as the integral over 24 hours of the total heat flux (sum of the indoor surface heat flux and of the transmitted solar irradiance) crossing the glazing system. To remove the effect of the solar irradiation of the previous day, the integration limits for its calculation were chosen from 07:00 to 07:00 + 1day during winter and from 05:00 to 05:00 + 1day during summer. This metric is most suited to comparing the performance of components that are tested under the same boundary conditions, whereas a proper selection of the days to analyse is required when comparing data that were not simultaneously measured. In the specific case, similar values of $E_{24,tot}$ for the reference technology ensured comparability among different datasets (Fig. 8). A data selection methodology for this purpose is detailed in Bianco et al. (2017a). The daily total energy can provide concise information for comparing the performance of several technologies, but additional information is needed to understand the dynamics of the system. As positive and negative energies are summed, an $E_{24,tot}$ e.g. close to zero does not imply constant adiabatic conditions throughout the day, but only that the energy losses are balanced by the energy gains.

$$E_{24,tot} = \int_{t=07:00}^{07:00\ +1day} \left(\dot{q}_{surf} + I_{in}\right) dt$$

Equation 7

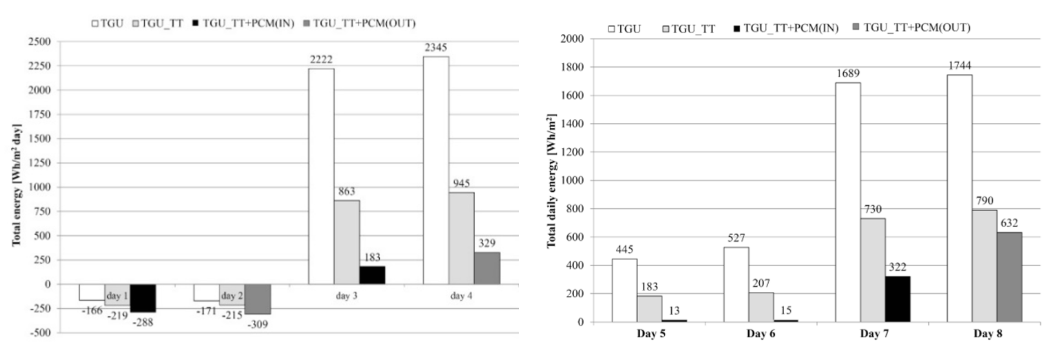


FIG. 8 Daily total energy crossing the technologies during selected winter days (left) *(Bianco et al., 2017a)* and summer days (right) (*Bianco et al., 2017b)*

4.1.2 Long-term total energy – $E_{n,tot}$ [Wh/m²/HDD]

Long-term total energy ($E_{n,tot}$ [Wh/m²/HDD], Bianco et al., 2017a) is defined as the total energy over a representative period, normalised over the heating (or cooling) degree days of the same period (HDD or CDD), extending the total daily energy concept in Section 4.1.1. In this way, when comparing more datasets, the influence on the results due to slight differences in the boundary conditions can be minimised. As for the total daily energy, the long-term total energy alone is not sufficient to understand the dynamics of the system, and the best comparability is obtained with simultaneous measurements. However, this metric provides more concise information of the seasonal performance of a system by removing the dependency on some of the boundary conditions of a single day, provided that a representative time period is analysed (Fig. 9). In fact, if this metric is able to normalise on the HDD or CDD, this does not account for solar radiation and, depending on the type of building and internal loads, the baseline temperature used to calculate HDD and CDD might change.

$$E_{n,tot} = \frac{\sum_{n=1}^{last\ day}(E_{24,tot})}{\sum_{n=1}^{last\ day}(\overline{\vartheta}_{in} - \vartheta_{out})}$$

Equation 8

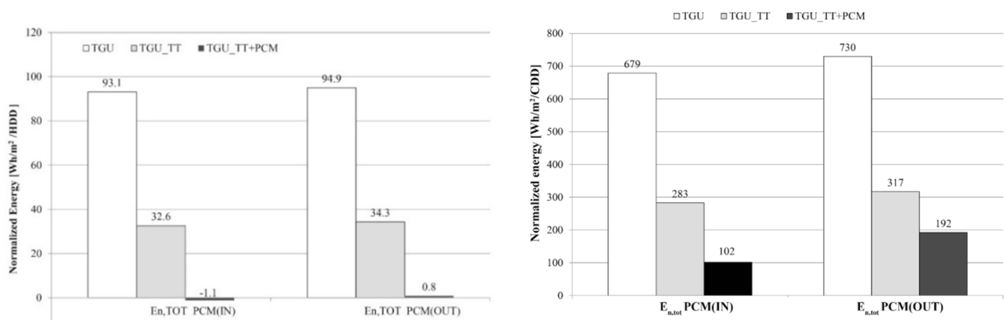


FIG. 9 Normalised total energy during a period in winter (left) *(Bianco et al., 2017a)* and summer (right) *(Bianco et al., 2017b)*

The considerations that could be drawn by the presented metrics supported the analyses of the hourly profiles of various physical properties. Although they provide overall and concise information, alone they cannot give sufficient insight on the dynamicity of the system, and a reference is always needed, especially for metrics that are not normalised on the boundary conditions.

5 PERFORMANCE METRICS FOR THE ADAPTIWALL PROJECT

The ADAPTIWALL project sought to develop new adaptive façade prototypes for building renovation (www.adaptiwall.eu). One of the prototypes consisted of a lightweight concrete with additives for efficient thermal storage and load bearing capacity. Depending on the extrinsic control of two hydraulic circuits (one exposed to the internal and one to the external environments), the lightweight concrete was charged or discharged (heated up or cooled down). The idea was to control the heat transfer to/from the indoor environment by storing heat in the thermal buffer and by controlling the flow rate in the two hydraulic circuits. The build-up of a representative construction is shown in Fig. 10.

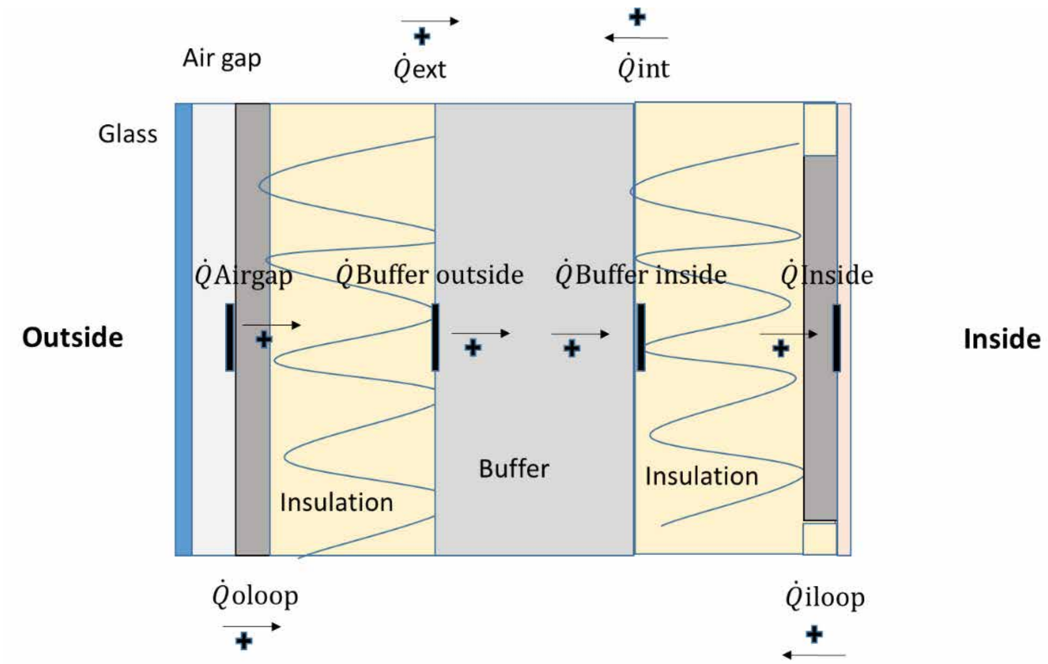


FIG. 10 Adaptiwall representative construction. Vertical black bars represent the heat flux plate meters integrated in the construction.

Four different small-scale ADAPTIWALL prototypes of $1m^2$ were tested at a test site in Algete (Madrid) and monitored from October 2015 to June 2016. The lightweight thermal buffer has a thickness of 16cm and is composed of lightweight concrete with incorporated phase change material (PCM) using a vacuum impregnation technique. The prototypes were comprised of a cladding made of 4mm clear float glass leaving a 15mm cavity. The total thickness of the panel was 40cm. The characteristics of the four prototypes are summarised in Table 1.

	PROTOTYPE 1	PROTOTYPE 2	PROTOTYPE 3	PROTOTYPE 4
Concrete type	C20/25, Lightweight concrete	C20/25, Lightweight concrete	C20/25, Lightweight concrete	C20/25, very fluid concrete (Consistency class S5)
Additives	Without PCM	Without PCM	PCM and alumina	Micro encapsulated PCM and alumina
Solution to avoid overheating	Fan	Sun screen	Sun screen	Sun screen

TABLE 1 Characteristics of Adaptivewall prototypes

The performance evaluation of ADAPTIWALL requires adequate metrics able to characterise the charging and discharging processes and their efficiencies. After a literature review, the metrics defined for ACTRESS by Favoino et al. (2016) have been considered as basis for the data analysis of the measurement data of the first test campaign. Metrics have been calculated using the heat fluxes defined as reported in Fig. 10. Q^*_{EXT} ,Q^*_{INT} , Q^*_{AirGap} and Q^*_{INSIDE} have been measured thanks to four heat flux plate meters integrated in the construction.$Q^*_{Buffer\ outside}$ and $Q^*_{Buffer\ inside}$ are equal to respectively Q^*_{EXT} , Q^*_{INT} but with different signs. Q^*_{OLOOP} and Q^*_{ILOOP} are heat fluxes of water loops in W/m^2 calculated from the difference between the measured inlet and outlet temperatures and from the mass flow rate estimation. Mass flow rates in the hydraulic loops are naturally circulated in these first prototype configurations. Hence, such flows have been calculated from the inlet-outlet temperature difference and from the calculation of the hydraulic losses along the pipes. Q^*_{Buffer} is calculated as in Equation 9. Q^*_{Buffer} is 0 at each time step if the right term of Equation 9 is lower than 0.

$$\dot{Q}_{Buffer} = (\dot{Q}_{OLOOP} + \dot{Q}_{EXT} + \dot{Q}_{INT}) \text{ [W/m²]}$$

Equation 9

5.1.1 Daily energy e24 for typical days

Daily energy e24 for typical days ($e_{-24,inside}$ is the heat flow through the border layer between the wall and the room integrated over 24 hours, as in Equation 10. This is analogous to the previous presented metric $E_{24,tot}$. Analogously for ACTRESS and SMARTGlass project, the integration start and end points need to be carefully selected, taking into account solar radiation, and charging and discharging processes. Moreover, the integrated daily energy can also be done for the other layers, giving useful information for the construction optimisation (Fig. 11 and 12 for Prototype 1 and 3, respectively).

$$e_{24,inside} = \int_{6am}^{6am+1day} \dot{Q}_{INSIDE}\, dt$$

Equation 10

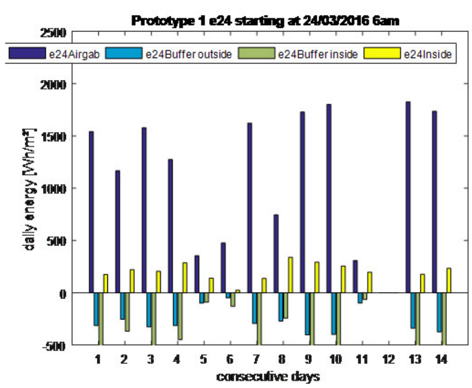


FIG. 11 e24 metric for Adaptiwall prototype 1

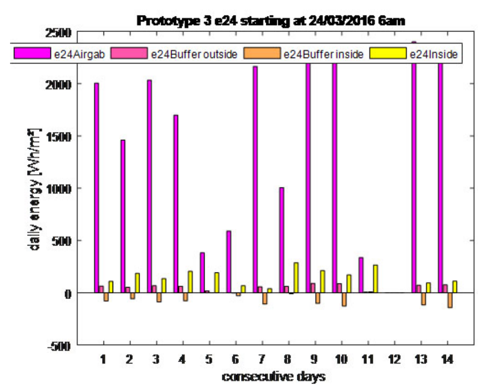


FIG. 12 e24 metric for Adaptiwall prototype 3

5.1.2 Usable heat efficiency η_{usable}

Usable heat efficiency (η_{usable}) indicates how much heat is discharged to the inside of the room compared to the charged heat inside the buffer over a 24 hour period, similarly to the definition in (5). The discharge period is defined as the period when the ILOOP of the switchable insulation is open. Fig. 13 shows the cumulated distribution function of η_{usable}. The values have a rather linear distribution and usually range between about 0.1 and 0.4 and they do not highlight any relevant improvements due to the use of PCM (prototypes 3 and 4). Prototype 4 has the most different behaviour. The reason for this is that PCM is integrated in the lightweight concrete with an aluminium casing (6.5% of total concrete weight). As a consequence, no mixing between concrete and PCM occurs. Hence, PCM activation happens with a time shift compared to the other prototype with impregnated lightweight aggregates directly in the concrete. Nevertheless, the best performance is reached by Prototype 4 with the maximum value around 0.42.

$$\eta_{usable} = \frac{\int_{start\ discharge}^{end\ discharge} \dot{Q}^{-}_{ILoop} dt}{\int_{6am}^{6am+1\ day} \dot{Q}^{+}_{Buffer} dt}$$

Equation 11

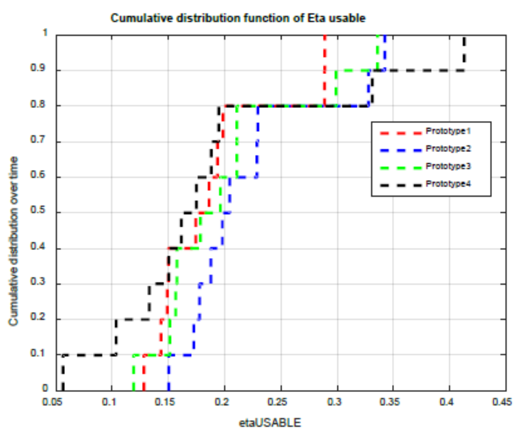


FIG. 13 η_{usable} cumulative frequency distribution for Adaptiwall prototypes

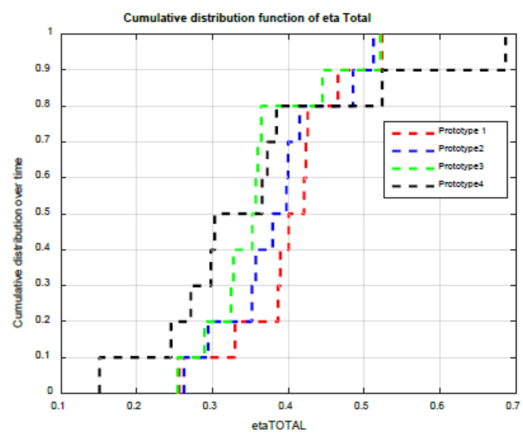


FIG. 14 η_{usable} cumulative frequency distribution for Adaptiwall prototypes

5.1.3 Total system heat efficiency η_{total}

Total system heat efficiency (η_{total}) expresses the overall efficiency of the system (Equation 6.1). It is the ratio of the heat supplied to the room by the heat charged into the buffer. Differently from η_{usable}, in this case the heat from the internal loop is integrated over 24 hours as the denominator, similarly to the definition in (6). Having a higher range of values compared to η_{usable} highlights the impact of the high thermal inertia. In other words, the internal loop also keeps distributing heat towards the indoor once the water flow stops. In Fig. 14, the same trend of Prototype 4 as for η_{usable} is observed (see explanation in the previous lines).

$$\eta_{TOTAL} = \frac{\int_{6am}^{6am+1\,day} \dot{Q}_{ILoop}^{-} dt}{\int_{6am}^{6am+1\,day} \dot{Q}_{Buffer}^{+} dt}$$

Equation 12

The values of η_{usable} and η_{total} are rather low, although comparable with the results from the ACTRESS prototype. In the case of η_{usable}, one reason could be that after the discharge period, as it was defined, the internal radiator is still warm and is further transmitting heat to the inside. Therefore, the way this parameter is defined, i.e. starting and ending time of the integration of the heat fluxes, needs to be carefully considered, and needs to be adapted to the dynamics of the system. Another relevant aspect to be more carefully considered is the effect of longterm accumulation of heat in the big thermal mass of the storage and of course the uncertainty of the mass flow in the inner and outer water loops.

6 PERFORMANCE METRICS FOR THE ACTIVE INSULATION PROJECT

Active Insulation is a dynamic insulation system that can either block or stimulate heat exchange between inside and outside (Koenders, Loonen, & Hensen, 2018). The system uses a structure of air ducts on the front and back sides of the insulation panel in combination with two low-voltage fans to actuate an air flow. The system is sealed with aluminium foil on both sides to create a closed system. When AIS is in the off-state (i.e. the fans are off), it acts as a regular insulation panel because the stagnant air contributes to achieving a high thermal resistance. However, when the fans are switched on, the insulation layer gets bypassed, thereby promoting heat exchange between inside and outside. Active Insulation can be used to provide passive cooling during cool summer nights, however, in this article the emphasis is on its potential to transfer solar heat gains during sunny winter days.

Next to measuring the system's U-value in the on and off state, the system can also be characterised by determining its efficiency in gaining heat from solar radiation. Detailed information about the heat fluxes throughout the whole structure are needed to determine this efficiency. To reduce the influence of any other parameters, an adapted TMY weather file for Amsterdam is used for this simulation-based characterisation. The outside air temperature has a fixed value to exclude influence of a fluctuating temperature on the heat transfer in the structure. Several fixed temperatures are studied, to determine the effect of outside temperature on efficiency. A typical sunny day was chosen to determine the efficiency of Active Insulation.

To determine the efficiency of the system, four daily heat flows through the structure are analysed: the heat flow at the outer surface ($Q_{outside\ surface,daily}$), the heat flow at the interface where the Active Insulation extracts the heat from the outer layer ($Q_{AI,outside,daily}$), the heat flow at the interface where the Active Insulation transfers the heat to the inner layer ($Q_{AI,inside,daily}$), and the heat flow at the inner surface ($Q_{inside\ surface,daily}$). Several efficiencies of the structure are calculated.

6.1 SOLAR HEAT GAIN EFFICIENCY, $\eta_{solar\ gain}$

Solar heat gain efficiency ($\eta_{solar\ gain}$) measures the efficiency between the absorbed solar radiation and the extracted heat. It can be determined by dividing the daily heat gains at the outer surface by the daily heat extraction of Active Insulation at the outer surface:

$$\eta_{solar\ gain} = \frac{\dot{Q}_{AI,outside,daily}}{\dot{Q}_{outside\ surface,daily}} * 100\%$$

Equation 13

6.2 THE SYSTEM EFFICIENCY, η_{system}

The system efficiency (η_{system}) quantifies the efficiency over the heat transferred by air in the Active Insulation system. It can be determined by dividing the daily heat extraction flux of Active Insulation at the outer surface by the daily heat gain flux of Active Insulation at the inner surface:

$$\eta_{system} = \frac{\dot{Q}_{AI,inside,daily}}{\dot{Q}_{AI,outside,daily}} * 100\%$$

Equation 14

6.3 OVERALL EFFICIENCY, $\eta_{overall}$

Overall efficiency ($\eta_{overall}$) measures the efficiency between the heat absorbed at the outer surface and what is actually transferred to the inside. It can be determined by dividing the daily heat flux at the outer surface by the daily heat flux at the inner surface:

$$\eta_{overall} = \frac{\dot{Q}_{inside\ surface,daily}}{\dot{Q}_{outside\ surface,daily}} * 100\%$$

Equation 15

Fig. 15 is a graphical representation of the heat flows and efficiencies described.

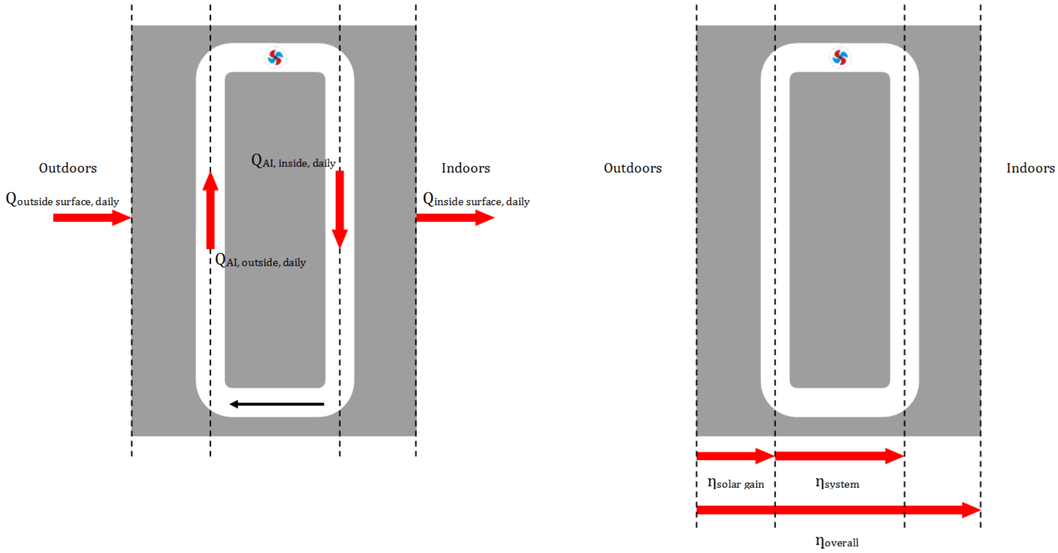


FIG. 15 Active Insulation - overview of heat flows and efficiencies

For this specific case, the results from the simulation are shown in Table 2, expressed in daily heat flow values into the zone. For comparative reasons, the analysis was carried out for cases in which Active Insulation is switched on during the day and for cases in which it is not used. Results indicate a significant increase in heat transferred to the inside when the Active Insulation system is activated.

JUNE 5, AMSTERDAM		$Q_{outside\ surface,daily}$ [Wh/m² daily]	$Q_{AI,outside,daily}$ [Wh/m² daily]	$Q_{AI,inside,daily}$ [Wh/m² daily]	$Q_{inside\ surface,daily}$ [Wh/m² daily]
0°C	Active Ins. OFF	2749.4	0.0	0.0	29.0
	Active Ins. ON	2749.4	303.3	298.9	298.7
5°C	Active Ins. OFF	2749.3	0.0	0.0	35.2
	Active Ins. ON	2749.3	336.3	331.5	335.0
10°C	Active Ins. OFF	2749.3	0.0	0.0	42.1
	Active Ins. ON	2749.3	374.6	369.3	376.5
15°C	Active Ins. OFF	2749.3	0.0	0.0	49.8
	Active Ins. ON	2749.3	419.3	413.4	424.4
20°C	Active Ins. OFF	2749.9	0.0	0.0	59.0
	Active Ins. ON	2749.9	472.3	465.6	483.6

TABLE 2 Active Insulation heat fluxes at different outside temperatures

Using the above mentioned equations, the efficiencies of the system can be determined with the given heat flows. For different exterior temperatures, the efficiencies are calculated and shown in Table 3. The efficiency of the Active Insulation system is constant at 98.5% for all temperatures. However, the solar gain efficiency is increasing with an increasing temperature. This is due to the fact that the difference between the surface temperature and the air temperature decreases, resulting in lower convective losses from the surface. The overall efficiency is mainly determined by the solar gain efficiency and thus also increases with temperature (Table 3).

OUTDOOR CONDITION	$\eta_{solar\ gain}$ [%]	η_{system} [%]	$\eta_{overall}$ [%]
0°C	11.03	98.56	10.87
5°C	12.23	98.57	12.19
10°C	13.63	98.57	13.70
15°C	15.25	98.58	15.44
20°C	17.17	98.59	17.59

TABLE 3 Efficiencies of the Active Insulation system for different temperatures

The results presented here show that characterising the Active Insulation system with one U-value or heat gain efficiency is not possible. The system is dynamic in such a way that its performance is influenced by dynamic weather data, but also by design and control parameters. Detailed simulations and experiments with prototypes will need to show the actual performance increase of Active Insulation for a specific situation.

7 DISCUSSION AND CONCLUSIONS

Using a combination of experiments and simulations, different indicators for adaptive opaque façades were identified. These are summarised in Table 4. These are not in the order of appearance in the paper (by project), but are ordered by similarity of characteristics (adaptive façade system technology, time frame etc.).

The main difference between the presented metrics, and the standard way to evaluate the performance of façades as U-value, G-value, and so on, is that the presented metrics cannot be calculated directly from physical characteristics of the materials adopted in a typical façade multi-layer system / construction, and do not have a general physical meaning. Instead, these metrics are derived from either experimental or numerical datasets, with the aim to quantify the performance of the system to achieve a certain objective (i.e. pre-heat supply air, reduce heat losses or gains, deliver solar radiation through an opaque component to the adjacent room etc.). As a result, most of the metrics devised in the presented projects are defined as dimensionless efficiencies or ratios over known quantities, which could be calculated based on boundary conditions and other physical parameters. It is worth noting the analogy in the definition of these metrics (or efficiency) between adaptive façade systems and Heating Ventilation and Air Conditioning (HVAC) systems, as both could have different operating modes and controls.

The main differences between the novel metrics presented are related to the dynamic nature of the adaptive system to be characterised. This can be divided into: i) short-term (sub-hourly or hourly metrics), related to the performance of fast reactive system, as ventilated cavity, either open or closed loop; ii) mid-term (daily metrics), related to the performance of systems that are storing and exchanging energy with the indoor environment over a daily cycle (mainly related to solar daily cycle and charge and discharge period of solar energy in the thermal mass of the building envelope); iii) long-term (monthly and seasonal metrics), adopted to normalise a certain metric over the boundary conditions of a longer period (heating or cooling season). Nevertheless, in order to provide a useful insight into the performance of dynamic façade systems and be normalised over a certain range / distribution of boundary conditions, short- and mid-term metrics can also be evaluated over a longer period, considering their cumulative distribution, as shown in the graphs presented in this paper.

With the mid-term metrics, particular attention should be paid to the starting and ending time of the integration of the heat flows, as these depend on the starting and ending time of the charge / discharge cycles and/or of the solar daily cycle (which is seasonally dependent).

Moreover, for long-term metrics, the definition of the baseline temperature of the HDD and CDD could depend on the type of climate (amount of available solar radiation as compared to the seasonal temperature variation), type of building (mainly related to the amount of internal thermal mass and endogenous occupation loads) and type / dynamics of the HVAC system adopted.

For most of the projects presented, the metrics adopted are derived from experimental data, although when physical numerical models of the adaptive façade systems become available, a longer time series of data could be generated to calculate the performance metric, or the system could be tested in specific boundary conditions in order to understand their influence over the performance metric (cf. Active Insulation Project, Section 5). Although due to the complexity of adaptive façade components, physical models are not always available (Loonen et al., 2017) or reliable (Favoino et al., 2017).

It is unlikely that a single set of metrics can be adopted to satisfy all performance quantification needs for any kind of adaptive façade system, due to the intrinsic differences (also in terms of dynamics) of different technologies. Therefore, future work is needed to investigate the differences and common features between adaptive façade performance metrics, and to cross validate them between different projects / technologies and data-sets. The aim of such work would be, rather than to develop a specific metric, to develop a methodology to characterise the performance of adaptive façade systems. In fact, being able to quantify the performance of an adaptive façade system through specific metrics would allow an easier comparison with that of alternative adaptive façade systems and with that of traditional static building envelopes.

ADAPTIVE FAÇADE SYSTEM	#	METRIC [UNITS]		EQ.	REF.	PROJECT	DATA SOURCE	TIME FRAME
Ventilated Cavity – Open Loop	1	*Dynamic insulation efficiency –* ε	[-]	(1)	Corgnati et al. (2007)	ACTRESS	Experimental	Sub-hourly, Hourly, Cumulated frequency over longer period
	2	*Pre-heating efficiency –* η_{PH}	[-]	(2)	Di Maio and Van Passen (2001)			
Closed Cavity	3	*Thermal buffer efficiency –* η_{TB}	[-]	(3)	Favoino et al. (2013)			
Ventilated cavity - Closed Loop	4	Solar heat gain efficiency - $\eta_{solar\ gain}$	[-]	(11)	Koenders et al. (2018)	ACTIVE INSULATION	Simulation	
	5	The system efficiency - η_{system}	[-]	(12)				
	6	Overall efficiency - $\eta_{overall}$	[-]	(13)				
Opaque Solar LHTES*	7	*Utilization factor of the solar LHTES system –* η_{LHTES}	[-]	(4)	Favoino et al. (2016)	ACTRESS	Experimental	Daily (solar radiation/ charge-discharge cycles), Cumulated frequency over longer period
	8	*Utilization factor of the usable energy of the LHTES –* $\eta_{LHTES\text{-}Usable}$	[-]	(5)				
	9	Usable heat efficiency **–** η_{usable}	[-]	(5.1)	N/A	ADAP- TI-WALL		
	10	*Utilization factor of the OSM system –* η_{OSM}	[-]	(6)	Favoino et al. (2016)	ACTRESS		
	11	Total system heat efficiency – η_{total}	[-]	(6.1)	N/A	ADAP- TI-WALL		
Transparent Solar LHTES*	12	*Total daily energy – $E_{24,tot}$*	*[Wh/m²]*	(7)	Bianco et a. (2017a)	SMART- GLASS	Experimental	
Opaque Solar LHTES*	13	Daily energy – e24	*[Wh/m²]*	(10)	N/A	ADAP- TI-WALL		
Transparent Solar LHTES*	14	*Long-term total energy – $E_{n,tot}$*	*[Wh/m²/HDD]*	(8)	Bianco et a. (2017a)	SMART- GLASS		Monthly, Seasonal

** LHTES: Latent Heat Themal Energy Storage*

TABLE 4 Adaptive façade system metrics summary

Acknowledgements

This paper is dedicated to the memory of Dr. Lorenza Bianco, a bright and inspiring colleague who recently passed away, who contributed to most of the projects presented in this paper and who was an active part of the COST Action TU1403 – Adaptive Façade Network.

The research activities of the ACTRESS project (Section 3) were carried out in the framework of the Italian PRIN 2007, funded by the Italian Minister of Research and Education.

The research activities regarding the SMARTGLASS project (Section 4) were carried out in the framework of the regional POLIGHT project 'SMARTGLASS', funded by Regione Piemonte.

The research activities of the ADAPTIWALL project (Section 5) were carried out in the framework of the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 608808, and with the support of the project FACEcamp n. ITAT1039, funded by European Regional Development Fund and Interreg ITA AUT programme.

The European COST Action TU1403 'Adaptive Façades Network' (2014-2018, *http://www.tu1403.eu*) is gratefully acknowledged for financially supporting the research study and for providing excellent research networking between the involved authors, as well as with international experts.

References

Aldawoud, A. (2013). Conventional fixed shading devices in comparison to an electrochromic glazing system in hot, dry climate. *Energy and Buildings, 59,* pp.104-110.

Bianco, L. (2014). *Involucri trasparenti innovativi. Modellazione e sperimentazione su componenti dinamici e sistemi di facciata attivi*. [Innovative transparent envelopes. Modelling and experimentation on dynamic components in active façade systems]. (Doctoral Thesis), Politecnico di Torino, Torino, Italy. doi:10.6092/polito/porto/2548139

Bianco, L., Goia, F., Serra, V., & Zinzi, M. (2015). Thermal and Optical Properties of a Thermotropic Glass Pane: Laboratory and In-Field Characterization. *Energy Procedia 78,* pp.116–121. doi:10.1016/j.egypro.2015.11.124

Bianco, L., Cascone, Y., Goia, F., Perino, M., & Serra, V. (2017a). Responsive glazing systems: Characterisation methods and winter performance. *Solar Energy 155*, pp. 372–387. doi:10.1016/j.solener.2017.06.029

Bianco L., Cascone Y., Goia F., Perino M., & Serra V. (2017b). Responsive glazing systems: Characterisation methods, summer performance and implications on thermal comfort. *Solar Energy 158*, pp.819-836. doi: doi.org/10.1016/j.solener.2017.09.050

Corgnati S.P., Perino M., & Serra V. (2007). Experimental assessment of the performance of an active transparent façade during actual operating conditions. *Solar Energy 81:8*, pp.993-1013.

EN ISO (2007). ISO 13789:2007. *Thermal performance of buildings -- Transmission and ventilation heat transfer coefficients* -- Calculation method

DiMaio, F., & Van Passen, A.H.C. (2001). Modelling the air infiltrations in the second skin façade. In*: Proceedings of IAQVEC 2001 – The 4th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings*, 2-5 October 2001, Changsha (China), pp.873-880.

Favoino F., Goia F., Perino M., & Serra V. (2013). Experimental assessment of the energy performance of an advanced responsive multifunctional façade module, *Energy and Buildings*, Available online 19 September 2013, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2013.08.066

Favoino F., Goia F., Perino M., & Serra V. (2016). Experimental analysis of the energy performance of an Active, RESponsive and Solar (ACTRESS) façade module, *Solar Energy 133,* doi: 10.1016/j.solener.2016.03.044.

Favoino, F., Jin, Q., & Overend, M. (2017). Design and control optimisation of adaptive insulation systems for office buildings. Part 1: Adaptive technologies and simulation framework, *Energy 127,* pp.301-309. Retrieved from https://doi.org/10.1016/j.energy.2017.03.083.

Favoino, F., Overend, M., & Jin, Q., (2015). The optimal thermo-optical properties and energy saving potential of adaptive glazing technologies. *Applied Energy 156,* pp.1–15.

Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., & Ranzi, G. (2016). Shape morphing solar shadings: A review. *Renewable and Sustainable Energy Reviews*, vol. 55(C), pp. 863-884. New York: Elsevier.

Goia, F., Perino, M., & Serra, V. (2013). Improving thermal comfort conditions by means of PCM glazing systems. *Energy and Buildings 60,* pp.442–452. doi: 10.1016/j.enbuild.2013.01.029

Goia, F,. Perino, M., & Serra, V. (2014). Experimental analysis of the energy performance of a full-scale PCM glazing prototype. *Solar Energy 100*, pp.217–233. doi: 10.1016/j.solener.2013.12.002

Goia, F., & Serra, V., (2018). Analysis of a non-calorimetric method for assessment of in-situ thermal transmittance and solar factor of glazed systems. *Solar Energy 166*, pp.458–471. doi: 10.1016/j.solener.2018.03.058

Jin, Q., Favoino, F., & Overend, M., (2017). Design and control optimisation of adaptive insulation systems for office buildings. Part 2: A parametric study for a temperate climate. *Energy 127*, pp.634–649. doi:10.1016/j.energy.2017.03.096

Koenders, S., Loonen, R.C.G.M., & Hensen, J.L.M. (2018). Investigating the potential of a closed-loop dynamic insulation system for opaque building elements. *Energy and Buildings 173*, pp.409-427. doi: 10.1016/j.enbuild.2018.05.051

Loonen R.C.G.M., Favoino F., Hensen J.L.M., & Overend, M. (2017). Review of current status, requirements and opportunities for building performance simulation of adaptive façades, *Journal of Building Performance Simulation*, doi:10.1080/19401493.2016.1152303

Loonen, R.C.G.M., Singaravel, S., Trčka, M., Cóstola, D., & Hensen, J.L.M., (2014). Simulation-based support for product development of innovative building envelope components. *Automation in Construction 45*. doi:10.1016/j.autcon.2014.05.008

Loonen, R.C.G.M., Trčka, M., Cóstola, D., & Hensen, J.L.M., (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews 25*, pp.483–493. doi:10.1016/j.rser.2013.04.016

JOURNAL OF FACADE DESIGN & ENGINEERING

VOLUME 6 / NUMBER 3 / 2018

TU DELFT OPEN
ISSN PRINT 2213-302X
ISSN ONLINE 2213-3038