JANUARY 17TH 2019 – MUNICH

POWERSKIN CONFERENCE

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The building skin has evolved enormously over the past decades. Energy performance and environmental quality of buildings are significantly determined by the building envelope. The façade has experienced a change in its role as an adaptive climate control system that leverages the synergies between form, material, mechanical and energy systems in an integrated design.

The PowerSkin Conference aims to address the role of building skins to accomplish a carbon neutral building stock. Topics such as building operation, embodied energy, energy generation and storage in context of envelope, energy and environment are considered. The 2019 issue of the conference PowerSkin focuses on the digital processes in façade design and construction, showcasing presentations about recent scientific research and developments in the field.

The **Technical University of Munich**, Prof. Dipl.-Ing. Thomas Auer, **TU Darmstadt**, Prof. Dr.-Ing. Jens Schneider and **TU Delft**, Prof. Dr.-Ing. Ulrich Knaack are hosting the PowerSkin Conference in collaboration with the trade fair **BAU 2019**, supported by the national funding initiative **Zukunft Bau (BBSR)**. It is the second event of a biennial series. On January 17th, 2019, architects, engineers, and scientists present their latest developments and research projects for public discussion.

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PREFACE

The building skin has evolved enormously over the past decades. Energy performance and the environmental quality of buildings are significantly determined by the building envelope. The façade has experienced a change in its role as an adaptive climate control system that leverages the synergies between form, material, mechanical and energy systems in an integrated design.

The PowerSkin Conference aims to address the role of building skins to accomplish a carbon neutral building stock. Topics such as building operation, embodied energy, energy generation and storage in the context of envelope, energy and environment are considered. The 2019 issue of the PowerSkin Conference focuses on the digital processes in façade design and construction, showcasing presentations about recent scientific research and developments in the field. The main theme about digital tools and methods in façade design and construction is the overarching topic that combines the three subjects:

- Envelope: The building envelope as an interface for the interaction between indoor and outdoor environment. This topic is focused on function, technical development and material properties.
- Energy: New concepts, accomplished projects, and visions for the interaction between building structure, envelope and energy technologies.
- Environment: Façades or elements of façades, which aim for the provision of highly comfortable surroundings where environmental control strategies as well as energy generation and/or storage are an integrated part of an active skin.

The three universities Technical University of Munich, TU Darmstadt, and TU Delft are signing responsible for the organization of the conference. We have to thank the authors and speakers for their contribution and our teams for doing such a good job in organizing this event. Finally we have to thank our sponsors for their support and the Messe München, which is so kind to give us the platform to organize such an event at their tradeshow BAU and by that create a link between academia and practice.

Thomas Auer,
Ulrich Knaack,
Jens Schneider,

the conference hosts.

SCIENTIFIC COMMITTEE

Prof. Dipl.-Ing. Thomas Auer

Trained as a Process Engineer at the Technical University in Stuttgart, Thomas is a partner and managing director of Transsolar GmbH, a German engineer-ing firm specialized in energy efficient building design and environmental quality with offices in Stuttgart, Munich, Paris and New York. In January of 2014 Thomas became Professor for building technology and climate responsive design at TUM. Thomas collaborated with world known architecture firms on numerous international design projects and competitions. A specialist in the fields of inte-grated building systems and energy efficiency in buildings as well as sustainable urban design, Thomas has developed concepts for projects around the world noted for their innovative design and energy performance – an integral part of signature architecture. The office tower for Manitoba Hydro in down-town Winnipeg, Canada, is considered one of the most energy efficient high-rise buildings in North America. Lower Don Lands, Toronto, is going to be among the first carbon neutral districts in North America. Outside of Transsolar, Thomas taught at Yale University and was a visiting professor at the ESA in Paris and other Universities. He speaks frequently at conferences and symposia. In 2010 Thomas received the Treehugger "best of green" award as "best engineer".

Prof. Dr.-Ing. Ulrich Knaack

Ulrich was trained as an architect at the RWTH Aachen University, Germany. After earning his degree he worked at the university as a researcher in the field of structural use of glass and completed his studies with a PhD.
In his professional career Ulrich worked as an architect and general planner in Düsseldorf, Germany, succeeding in national and international competitions. His projects include high-rise and office buildings, commercial buildings and stadiums.
In his academic career Ulrich was professor for Design and Construction at the Hochschule OWL, Germany. He also was and still is appointed professor for Design of Construction at the Delft University of Technology / Faculty of Architecture, Netherlands, where he developed the Façade Research Group. In parallel Ulrich is professor for Façade Technology at the TU Darmstadt / Faculty of Civil engineering in Germany where he participates in the Institute of Structural Mechanics + Design.
Ulrich organizes interdisciplinary design workshops and symposiums in the field of facades and is author of several well-known reference books, articles and lectures.

Prof. Dr.-Ing. Jens Schneider

Jens is a full professor for structural engineering at the Institute of Structural Mechanics and Design, TU Darmstadt, Germany. After his studies in civil engineering in Darmstadt and Coimbra, Portugal, Jens received his PhD from TU Darmstadt in 2001 in a topic about structural glass design and impact loading.
From 2001-2005 Jens worked at the engineering office Schlaich, Bergermann and Partner where he was involved in the structural design of complex steel, glass and concrete structures. In 2006 Jens was appointed as an authorized sworn expert on glass structures, in 2007 to the position of a professor for structural engineering in Frankfurt and in 2009 to his current position at TU Darmstadt, where Jens is currently the dean of the faculty for civil and envi-ronmental engineering. Since 2011, Jens is also partner in his engineering office SGS GmbH in Heusenstamm in Frankfurt, Germany. Since 2015, Jens leads the European project group for the preparation of the new Eurocode 11 „Structural Glass".
Jens is specialized in structural mechanics of glass & polymers, façade structures, structural design and synergetic, energy-efficient design of façades and buildings.

Prof. Anne Beim, Ph.D.

Anne is a professor in architecture at The Royal Danish Academy of Fine Arts School of Architecture. She is the head of CINARK - Centre for Industrialized Architecture and initiator as well as co-chair of the graduate program: Settlement, Ecology and Tectonics. Anne received her M.Arch. in 1990 and holds a Ph.D. in architecture, gained in 2000 from the Royal Danish Academy of Fine Arts School of Architecture. Part of her Ph.D. studies has been conducted under Professor Marco Frascari and Professor David Leatherbarrow as a visiting scholar at PennDesign, University of Pennsylvania. Her research is particularly focusing on how architectural ideas translate into the world of constructions defined by building culture and tectonics – the latter considered as an essential part of the architectural creation and in regard of its ecological dimension. The challenges provided by the rational pragmatism of the construction industry, for which deep knowledge into material qualities, construction principles and detailing are important design parameters of the architect, have her special attention. Anne has managed and conducted several research projects and published a number of books and scientific articles within this field.

Prof. Dr.-Ing. Tillmann Klein

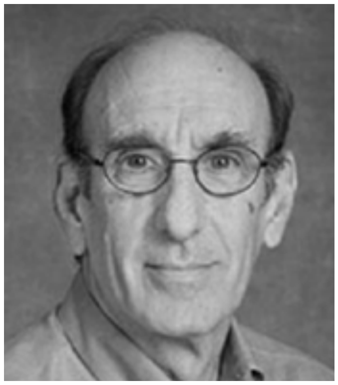
Tillmann studied architecture at the RWTH Aachen, completing with a degree in 1994. From then on he worked in several architecture offices, later focusing on the construction of metal and glass facades and glass roofs.
Simultaneously he attended the Kunstakademie in Düsseldorf, Klasse Baukunst, completing the studies in 2000 with the title "Meisterschüler". In 1999 he was co-founder of the architecture office Rheinflügel Baukunst with a focus on art related projects. In 2005 he was awarded the art prize of Nordrhein-Westfalen for young artists.
Since September 2005 he leads the Facade Research Group at the TU Delft, Faculty of Architecture and since 2008 he is director of the façade consulting office Imagine Envelope b.v. in Den Haag. Tillmann is editor in chief of the scientific open access ´Journal of Façade Design and Engineering´ and since 2015 he is guest professor for Design and Building Envelopes at the Technical University of Munich.

Prof. Dr. Madjid Madjidi

Madjid is a professor for Computer Based Design for Building Systems at the University of Applied Sciences in Munich. He gives lectures in numerical methods, computer based engineering, building system simulation and computational fluid dynamics.
Madjid studied Aeronautics Engineering at University of Stuttgart from 1981 to 1988. After receiving his diploma he moved to the field of Energy Technologies where he wrote his PhD thesis in 1996 on model based fault detection and optimization of air-conditioning systems. During his years at University of Stuttgart and later as a consulting engineer Madjid took part in several projects of the International Energy Agency dealing with transient system simulations, building energy management, fault detection and diagnosis methods and reversible heat pumps. Since 1996 he is running a consulting office for indoor climate solutions and renewable energy concepts. Madjid is an honored lifetime member of the Verein Deutscher Ingenieure (VDI), member of the editorial board of the international journal Building Simulation and member of the scientific committee of the international conference System Simulation in Buildings.

Prof. Dr. Alberto Raimondi

Alberto is a junior professor at the Faculty of Architecture University of Roma Tre, Italy. Since 2015, he is also a guest lecturer at the Technical University of Munich.
Alberto teaches construction design, materials and components, as well as building technology at the Faculty of Architecture of Roma Tre. He is involved in international and national researches. His main activities and responsibilities are research and experimentation in the field of the technology of architecture, focusing on innovation in construction (structural design, BIM for design control and construction process) and sustainability design (building materials, technologies to improve the energy efficiency and quality of environmental control systems in buildings). Alberto introduced the use of BIM in the courses to improve the students' control of design and construction. In the last years the research is focused on the issue of building retrofitting.



Stephen Selkowitz, MFA

Stephen has 40 years of experience in the field of building energy and environmental performance, with an emphasis on research, development, and deployment of energy efficient technologies, integrated building systems and sustainable design practices. He is Senior Advisor for Building Science at Lawrence Berkeley National Laboratory (LBNL). The research program balances R&D with an aggressive technology transfer effort so that research results are effectively adopted by the building industry. Stephen participates in a wide range of building industry, government, and professional activities in the U.S. and internationally, is a Scientific Advisor to four building science programs globally, and author/co-author of over 170 publications, four books and holds two patents. In 2012 he was the recipient of the first LBNL Lifetime Achievement Award for Societal Impact and in 2014 he received the McGraw Hill/ENR 2014 Award of Excellence for "relentlessly working to reduce the carbon footprint of buildings and for moving the nation towards better building performance." Stephen holds an AB degree from Harvard College with a major in Physics and an MFA in Environmental Design from CalArts.

Prof. Dipl.-Ing. Andreas Wagner

Andreas studied mechanical engineering at the University of Karlsruhe before he worked as a researcher at the Fraunhofer ISE in Freiburg for 8 years.
His main fields of research included solar thermal systems and energy concepts for buildings. Since 1995 he is a full professor for Building Physics and Technical Building Services at the Faculty of Architecture of the Karlsruhe Institute of Technology (KIT) and head of the Building Science Group.
His research focuses on monitoring and performance analysis of energy efficient buildings as well as comfort and occupant satisfaction at workplaces. From 2000 to 2004 and 2012 to 2015 Andreas was dean of the KIT Department of Architecture. Andreas is member of different editorial boards as well as of numerous committees. In addition, he is the co-founder of the consultancy firm ip5 in Karlsruhe.

Prof. Dr.-Ing. Frank Wellershoff

Frank is a full professor at the HafenCity University, Hamburg in Germany, since 2011. His research is focused on the structural and physical performance of façade systems and building envelopes.
Frank received his diploma degree in civil engineering from the University of Bochum in 1994 and started his professional career as a project engineer for steel and concrete structures at CSK Engineers, Bochum. From 1997 to 2005 he researched at the Institute of Steel and light-weight Structures, RWTH Aachen University. Here, he conducted several projects in the fields of wind engineering, structural glass application and façade systems. Frank received his Ph.D. in 2006 with the topic of stabilization of building envelopes with the use of the glazing.
From 2005 to 2011 he was team leader for engineering at Permasteelisa/Gartner, a global operating façade contractor. In this function Frank was responsible for the engineering design of more than 30 high end façades.

KEYNOTES

Matthias Sauerbruch

THE ADAPTIVE FAÇADE APPROACH

Matthias Sauerbruch is an architect and partner of Sauerbruch Hutton architects. Founded in 1989 in London, UK, and established in 1991 in Berlin, Germany, Sauerbruch Hutton is one of the most important and experienced architectural firms in sustainable building. Their integrated design approach combines functionality and environmental performance with sensuality and intuition.

Matthias Sauerbruch studied architecture at the Hochschule der Künste Berlin, Germany, as well as at the Architectural Association London, UK. While being a practicing architect he was professor at the TU Berlin, the Academy of Fine Arts Stuttgart, the Harvard Graduate School of Design, and the Universität der Künste Berlin. Matthias Sauerbruch is co-founder of the DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen), member of the city designing commission Munich, and board member of the KW Institute for Contemporary Art Berlin. He is Honorary Fellow of the American Institute of Architects and director of the Sektion Baukunst of the Akademie der Künste, Berlin.

Sauerbruch Hutton architects realize individual and sustainable solutions for a wide range of projects. The enjoyment of the sensuality of space and material as well as the mastery of up-to-date technology and the intelligent use of existing resources of every kind are the focus of their work.

Built works range from the much-noted Brandhorst Museum in Munich, Germany, to the Federal Environmental Agency in Dessau, Germany, which represents a benchmark building for the sustainable design of offices. A whole series of such projects for private and public clients are currently designed and constructed in Germany and Europe.

Their projects are always inspired by and tailored to the specifics of the site, the brief and the client. Since they consider architecture to be a process of dialogue they intimately involve selected experts and consultants in every stage of the design process. Their work has been awarded numerous national and international prizes.

Sauerbruch Hutton architecture is individual but at the same time developed out of a response to generic contemporary conditions. Their innovative approach to sustainability has formed a developing method to the materiality and the appearance of their projects. Early on, there was a desire to emphasize passive design strategies such as the utilization of daylight, solar and daylight control, as well as natural ventilation. The use of adaptive façades in order to control environmental qualities is a common feature in buildings designed by Sauerbruch Hutton architects (e.g. GSW high rise building in Berlin or KfW Westarkade in Frankfurt, Germany).

KFW-Westarkade, Frankfurt, Germany @Jan Bitter

There is a tendency that adaptive façades require moveable parts and advanced control strategies for passive systems as well as supplemental active systems are required for the extreme periods in winter and summer. This leads to an overall complexity, which often causes issues during commissioning and even in operation. As a result a low-tech approach became the driver for the design of the Environmental Agency in Hamburg, Germany. Less adaptive façade elements and less mechanical systems – combined with a manual control whenever possible – lead to a very robust building. At the same time the minimized building systems still provide appropriate environmental qualities and an increased user satisfaction.

The examples show that the industry needs to critically reflect the adaptive façade approaches, which have been developed mainly over the past two decades. Issues with the building management system – combined with an instantaneous change of environmental conditions – often bother the user instead of optimizing environmental qualities.

The next generation of adaptive façade systems needs to build up on so called autoreactive systems, such as glazing systems, which slowly change glass properties e.g. over the temperature. In addition it needs systems that trust the human sensorial perception and in essence gives the user the ability to interact easily instead of a full reliance on building control systems.

Neil Thomas

SUSTAINABILITY IN CONSTRUCTION

Neil Thomas is the Director of Atelier One, which has been described as 'the most innovative engineering practice in the UK'. This innovation covers high-level research and implementation for materials in an enormous scale and a variety of projects, often providing specialist advice to larger consulting practices.
Neil frequently conducts public lectures at institutions such as RIBA, the V&A, and many Universities both in the UK and overseas. As well as teaching a structures course at Yale University and MIT, Neil recently delivered a Mastercalss at the university of Hamburg, and is a regular tutor at the Architectural Association, UCL and the Royal College of Arts. Most recently Neil has been appointed by Leeds University as a member of a Steering Group to develop a new Architectural Engineering course.

Atelier One has developed a form of practice over 25 years with a unique mentality. Whilst remaining small (see Chris Wise's article 'Why Small Practices are Genetically Important'), we have worked on projects of hugely varying type and scale. This works due to one basic principle, collaboration. We have developed a significant number of expert connections, in numerous different fields and we continue to expand these transient alliances. We are currently working with Chris Williams (shell structure expert), Max Irvine (dynamicist) , Rick Lindsey (rammed earth specialist), Frederic Opsomer (LED video screen pioneer) and Jorg Stamm (bamboo guru) to name but a few. This model has enabled us to approach projects with the unique perspective of a group of open-minded thinkers with the guidance of experts.

This collaboration extends to us forming close ties with academics and universities which gives the opportunity to improve learning and innovation within the industry. Directors Neil Thomas and Aran Chadwick have dedicated much of their time in this field. Both Aran and Neil teach at Yale University and most recently have been invited to teach at Massachusetts Institute of Technology. They are also external examiners for the Architectural Association. Both directors are keen to encourage young engineering talent and regularly offer internships to enthusiastic students.

The winning entry for the British Pavilion at the Dubai Expo 2020 with Es Devlin

Since our inception, one of the core aims of the practice has been to endeavour to improve sustainability in construction. Our approach is twofold:

- We strive to design the most efficient structural solutions using the least resources. We continually research materials, systems and construction methods in order to reduce energy consumption and regulate harmful emissions.
- We embrace all new technologies and carefully integrate them where appropriate to achieve a more environmentally responsible end solution.

PART 1 // ENVIRONMENT

Adaptive Bricks: Potentials of Evaporative Cooling in Brick Building Envelopes to Enhance Urban Microclimate

Philipp Molter[1], Jakob Fellner[2], Kasimir Forth[3], Ata Chokhachian[4]

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2 Technical University of Munich, Munich, Germany
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Abstract
Over the history of human settlements, approximately 30% of the world's population lived in brick made structures by 1990. It is also projected that the brick product segments will raise 3.5% during 2017-2027 and it is anticipated to dominate over the forecast period. So far, energy regulations have pushed the innovation of bricks towards better U-values especially in northern and central Europe however there has been less attention to see brick as a climate active material able to improve microclimate conditions. Within this regard this research is investigating the potentials of irrigated solid bricks as a component for climate adaptive façades able to enhance urban microclimate in urban canyons. The study shaped in two layers including field measurements and simulations. An experiment setup of façade panel is demonstrated to test different irrigation scenarios under varying environmental conditions and hours of the day to quantify surface temperatures and intensity of evaporative cooling effect. The results are validated with transient hygro-thermal simulation models in WUFI. The results show that in average wet bricks can have 7 °C lower surface temperatures compared to dry ones. Also the color of the bricks is influencing the temperature curve where the difference of 5.4 °C recorded between light and dark colored ones.

Keywords
irrigated bricks, microclimate, outdoor comfort, evapotranspiration

1 INTRODUCTION

"When we talk about brick, people think that we talk about tradition but it is all about innovative approach giving the brick a new meaning and new appearance."

Wang Shu, Brick Award 14

In the last centuries, history of human settlement was very much related to the use of brick as a key element for shelter as structure of architectural space (Serena, 2012). Since the very beginning of human settlement, sun dried mud and later burned bricks made out of clay have been used to build shelter and buildings all over the globe. Sun dried mud bricks are a common building material across the globe, found in many archaeological sites in the Old World over ca. 11000 years ago (Friesem, Karkanas, Tsartsidou, & Shahack-Gross, 2014). First traces are reported from Neolithic settlements in Anatolia and the Levant (Cauvin, 2000). Clay was the predominant building material in architecture of the Neolithic era which has been called the "Age of Clay" (Schmandt-Besserat, 2015; Stevanović, 1997). Due to their robustness, bricks have been widely used as waterproof materials in aqueducts, bridge sand cisterns since early Hellenistic time (Uğurlu & Böke, 2009). Later, bricks have been further developed and especially the invention of burned bricks round 4000 BC, durability, resistance and structural performance has increased the use of this technology. The widely use of mud-bricks as a key element in prehistoric architecture and the following centuries is related to its modular and highly flexible use and adaptability to various applications allowing for a high degree of design freedom and structural performance (Oates, 1990).

According to statistics in 1990, approximately 30% of the world's population lived in earthen brick made structures (Coffman, Agnewl, Austin, & Doehnel, 1990). In the last years brick architecture has experienced a revival and will grow even further. As said by Compound Annual Growth Rate, (CAGR) for the brick product segment the estimation is to raise 3.5% during 2017-2027 and it is anticipated to dominate over the forecast period (TMRGL, 2017).

This success of monolithic walls built from a single material as an approach captivates builders and planners by its simplicity and the avoidance of complicated details (Wernery, Ben-Ishai, Binder, & Brunner, 2017). The mentioned advantages of brick construction are also subject of further research in digital fabrication with robots enabling architects to directly control complex geometries in construction. Due to its close relation to common construction practice, digital fabrication allows for the control of the micro and macro structure of a building component, performance optimization through the design of the cross section (Bonswetch, Kobel, Gramazio, & Kohler, 2006). Therefore, this technology is supposed to increase the spread of brick construction in architectural context. However, since the 1980s, energy regulations have pushed the innovation of bricks towards better U-values especially in northern and central Europe. Thus, the latest developments have been pushed towards insulating bricks since they incorporate both the structural and the thermal functions of the building envelope (Wernery et al., 2017).

The work of this research focuses on the potentials of brick as a climate active material improving urban (thermal) comfort conditions. Research and practice has already proved that brick is one of well performing material for climate control due to its high thermal capacity and thermal mass effect (Al-Sanea, Zedan, & Al-Hussain, 2012, 2013) nevertheless energy regulations have limited the innovation of bricks towards better thermal performance only. There have been various studies performed to understand thermal and optical performance of façade and pavement materials on microclimate of cities. The issue is important due to urban heat island phenomena described as temperature differences between downtown and suburbs. Due to decreased sky view factor in urban canyons as function of compactness and increased density of cities, the trapped heat and solar radiation keeps surface temperatures high even during night time. As consequence, the buildings that are dependent on night time cooling cannot recover and they cause significant health issues. The summer of 2003 could be relevant instance in Europe for the extreme heat wave that caused 15000 additional deaths in France (Ata Chokhachian, Santucci, & Auer, 2017).

Addressing the mention problems, this paper investigates application of innovative approach on the potentials of irrigated solid bricks as a component for climate adaptive façades aiming to enhance urban microclimate and outdoor comfort. The study shaped in two layers including field measurements and simulations. An experiment setup of façade panel is demonstrated to test different irrigation scenarios under varying environmental conditions and hours of the day to quantify surface temperatures and intensity of evaporative cooling effect. The results are validated with transient simulation models in WUFI.

2 BUILDING ENVELOPES AND IMPACT ON MICROCLIMATE

The phenomena of urbanization and industrialization concerning its effect on environmental change has been known and studied for many centuries all over the world. Addressing the topic of environmental change, we need to refer to relevant metrics depending on the context and scale. Urban Heat Island effect (UHI) is one of the widely investigated phenomena to measure the effect of urbanization and built environment on the climate of cities. It is one of the most common manifestations on urban climate studies and since its advent by Luke Howard (1818), it is still the topic of researchers in different regions of the world. UHI by definition is known as higher temperatures or heat content stored in urban areas caused due to the anthropogenic heat released from vehicles, power plants, air conditioners and other heat sources, and due to the heat stored and re-radiated by massive and complex urban structures which leads to deterioration of living environment and increase in energy consumptions (Rizwan, Dennis, & Liu, 2008).

As an example, Analysis of temperature trends for the last 100 years in several large U.S. cities indicate that, since ~1940, temperatures in urban areas have increased by about 0.5 - 3.0 °C. Typically, electricity demand in cities increases by 2 - 4 % for each 1 °C increase in temperature. Hence, we estimate that 5 - 10 % of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5 - 3.0 °C in urban temperatures (Akbari, Pomerantz, & Taha, 2001; Jandaghian & Akbari, 2018). It is found that for the city of Athens, where the mean heat island intensity exceeds 10 °C, the cooling load of urban buildings may be doubled, the peak electricity load for cooling purposes may be tripled especially for higher set point temperatures, while the minimum COP value of air conditioners may be decreased up to 25% because of the higher ambient temperatures (Mofidi & Akbari, 2017; Santamouris et al., 2001).

There has been several approaches toward UHI mitigation by designing proportional aspect ratio for street canyons which allows enough sky exposure for night time cooling or choosing proper materials for building envelopes depending on context and orientation of each façade. Studies show that brick façades with low reflectivity in comparison with heavily insulated envelopes can decrease extreme heat stress for pedestrians by 26% during the day time (Ata Chokhachian, Perini, Dong, & Auer, 2017). Additionally, there has been several studies about evaporative cooling potential of building envelopes where Han, Xu, and Qing (2017) explored the effect of two passive cooling systems, water-retaining bricks on roof and radiation shield on roof concluding that the maximum cooling capability can be achieved through on-roof water-retaining bricks. Another study explores the effects of a Moist Void-brick wall as passive microclimatic converter and the results show that the wall surface temperature are averagely lower than ambient air temperature by 5 °C over day time

(He & Liu, 2012). Addressing the wide spread of brick buildings as well as the mentioned problems with urban heat island and outdoor comfort, this paper proposes an architectural investigation on innovative approaches on the potentials of irrigated solid bricks as a component for climate adaptive façades. It is understood that the focus on this research is clearly an investigation as an architectural approach rather than an emphasis on building physics.

3 RESEARCH METHODOLOGY

The study approached with two complimentary methods of experiments and validation modeling. In order to evaluate the potentials of evaporative cooling with irrigated bricks following steps conducted: Measurements: In-situ measurements on evaporation cooling effects of irrigated bricks were taken on two different summer days in Munich. The measured data served as a base for thermal simulations in part 2 (Simulations).

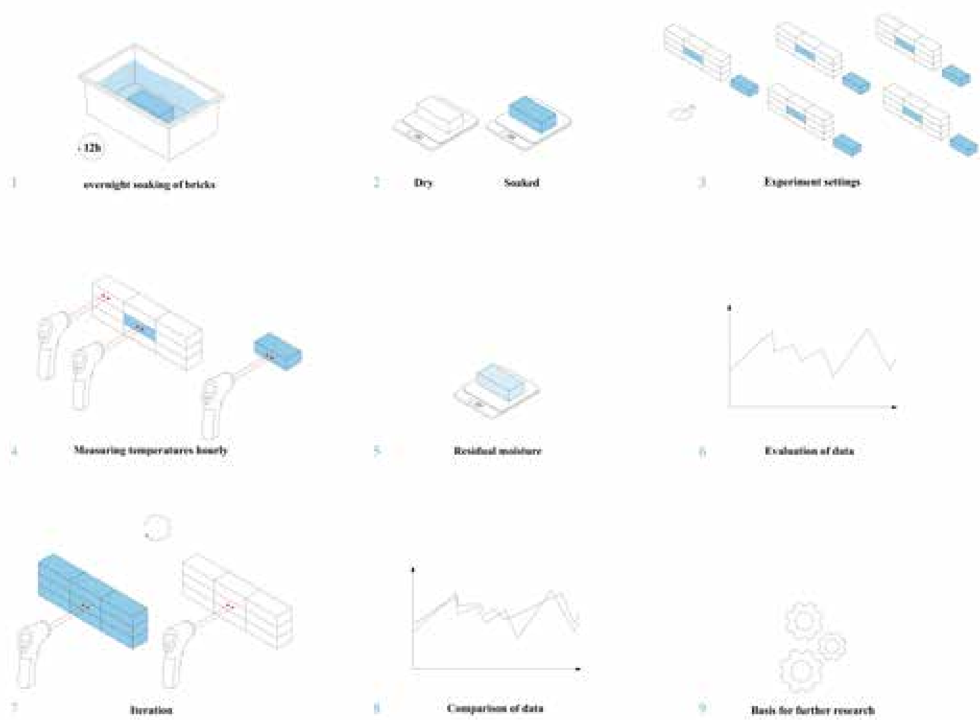

FIG. 1 Experiment setup and process of measurements

Numerical simulation: In order to validate the experiments thermal simulations in WUFI (Lengsfeld & Holm, 2007), a software developed by Fraunhofer institute were set up based on boundary conditions of the measurements. WUFI allows realistic calculations of heat and moisture transport in walls and other multi-layer building components exposed to varying environmental conditions. The outcome of the measurements and simulations lead to an investigation in constructive solutions for façade application of irrigated brick walls. Summary of methodology is illustrated in fig. 1.

3.1 MEASUREMENTS AND EXPERIMENT SETUP

The first investigation was an in-situ testing setup to measure and monitor evaporation potential of irrigated bricks exposed to solar radiation in an urban context. For this reason experiment setup of different brick types are built and tested over a day. The objects were monitored on two summer sunny days (03.07.2018 and 14.07.2018) on the rooftop terrace at 28 meters height above ground floor in the city center of Munich (48.135125 - 11.581981). The setup is done for different colors and densities of bricks based on concrete soil ground in full south orientation. Fig. 2 shows the experiment setup demonstration with 5 different brick types as: solid porous bricks in white (Passo), black (Pescara) Yellow (Lagoni), and red (Bologna) as well as red (Bologna) containing holes, each brick sized 240 mm x 115 mm x 71 mm.

FIG. 2 Experiment setup and process of measurements

The water suction capacity was varying between 1 – 7 % depending on the color of bricks: white and black: 2% - light red: 4%. A small wall was layered in a row of three bricks in length and three layers in height. The tenth brick was placed besides allowing more solar exposure of surfaces. The middle bricks as of each series as well as the isolated one laying aside were watered in a bucket for twelve hours (Fig. 3) and they were weighted before and after they were soaked. A parallel recording of weather data was done using Ahlborn Almemo System, and WinControl V6 Software. In order to validate the measured data, a second weather station has been used which is installed on the roof top at same height of an adjacent building in 300m distance. (https://www.meteo.physik.uni-muenchen.de/wetter/index.html). The recorded weather data included: global radiation, diffuse radiation air temperature, wind speed, relative humidity. Measurements as test series were taken on two different days, 3rd and 14th of July 2018 from 9 am till 5 pm with time step of 2 minutes (Fig. 3).

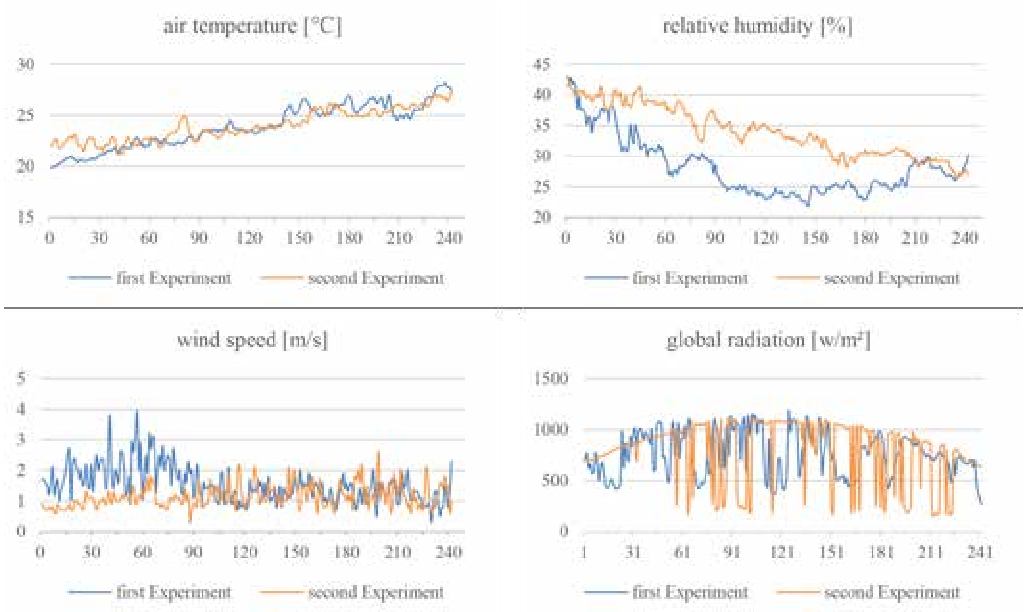

FIG. 3 Recorded weather data for 2 experiment days

For the experiment setup five walls out of different bricks were positioned on concrete base. Each experiment unit consisted of 10 bricks; of which 9 made up the tested wall and one was tested independently under the same boundary conditions to see the full evaporative capabilities of a singular brick. Therefore, two bricks were left to soak in water tub overnight to have a maximum water content. The bricks were weighted before and after they were soaked. One soaked brick was positioned centrally in the wall surrounded by 8 briefly wetted bricks. The other soaked brick was tested individually. The brick in the upper left corner of the 9 bricks in a wall was also measured (Fig. 4). Surface temperature of wet and dry bricks was measured with infrared thermometer for each brick in the middle of a 9-brick-wall (Fig. 5). Instead of hourly measurements to increase the accuracy of the experiment the bricks were monitored every half hour, including the weight.

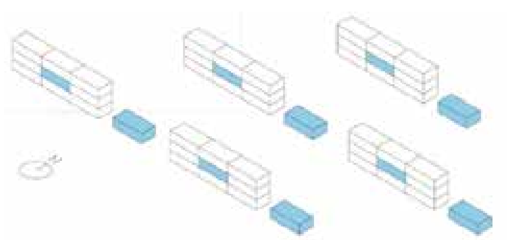

FIG. 4 Experiment configuration and location of wet bricks

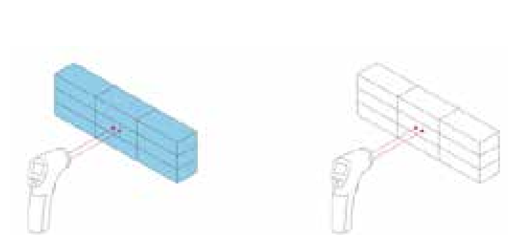

FIG. 5 Surface temperature was measure by infrared thermometer for both wet and dry bricks

On the first day (3rd of July), the air temperature showed a slow increase from 20 °C in the morning until 28 °C in the afternoon. In average the wind speed was 2 m/s in the morning with more variations compared to afternoon with average speed of 1.5 m/s. Several wind gusts were recorded showing a speeds of 3.8 m/s in the morning. The radiation was from time to time slightly overcast by some clouds. The global radiation, addition of direct and diffused, raised its maximum at 13:07 with 1178 W/m2. Highest direct solar radiation was recorded at 13:29 up to 937 W/m^2. The indirect radiation reached its maximum at 11:11 with 462 W/m^2. The values for relative humidity was decreasing until 12 and was increasing by late afternoon. Since the temperature was still raising, the absolute humidity was increasing significantly.

On the second round of experiment (14^{th} of July) temperature values showed to be slightly higher in the beginning of the measurements, however, over the course of day it was comparable with the first day. In the morning of the first experiment, the wind was stronger, whereas the day of the second experiment had calmer wind speeds with less variations. Overall, the difference in weather on both experiment days was not exceptionally significant. The global radiation reached high levels very quickly, due to the clear sky before 11 am. Later on, the clouds reduced the radiation down to 200 W/m2. Overall, the solar radiation showed higher values in comparison to the first day. Relative humidity was decreasing continuously and the absolute humidity has likely remained similar. This was different in comparison to values of relative humidity received during the first experiment.

3.2 NUMERICAL SIMULATIONS

In order to certify the experiments, the modeling approach was deployed. The goal was to compare the simulation results with those of the detailed measurements for validating the simulation considering the surface temperature and the humidity within the bricks. After validation of the experiment, in the second step the simulation is transferred to another climate zones in order to estimate maximum potential of wet bricks in terms of evaporative cooling. Within this regard, in order to demonstrate the potential of improved microclimate with irrigated brick, the city of Madrid in Spain was chosen since it's known as a dense city and has hot summers. The method can be transferred to other potential climate zones and cities but this was not the main scope of this research. Fig. 6 show the overall process of coupling through measurements and simulations.

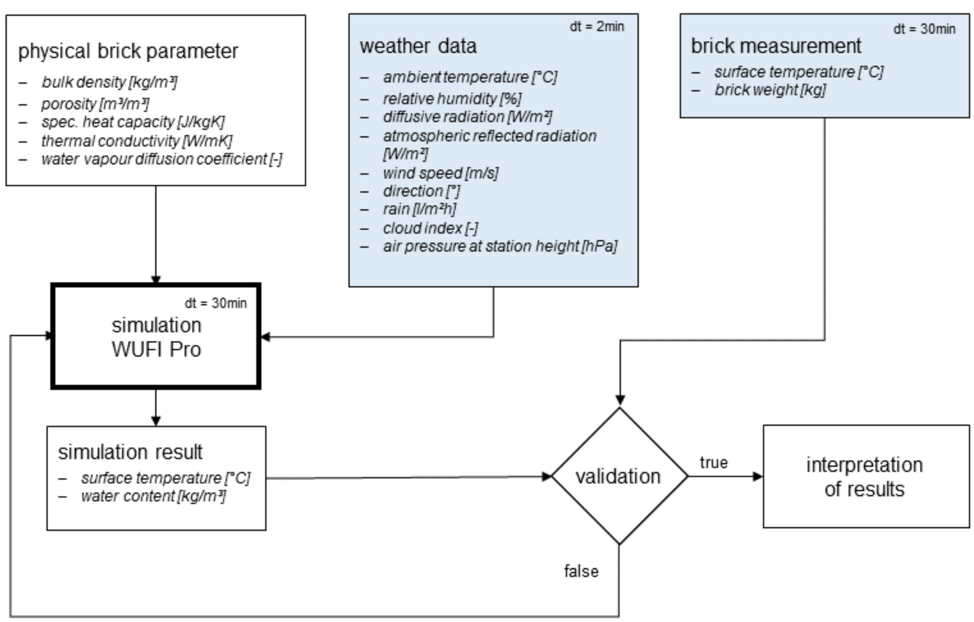

FIG. 6 The process of measurement validation with WUFI simulations

$$\frac{dH}{d\vartheta}\frac{\partial \vartheta}{\partial t} = \nabla * (\lambda \nabla \vartheta) + h_V \nabla * \left(\delta_p \nabla(\varphi \, p_{sat})\right) \qquad (1)$$

$$\frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t} = \nabla * \left(D_\varphi \nabla \varphi + \delta_p \nabla(\varphi \, p_{sat})\right) \qquad (2)$$

$dH/d\vartheta$	[J/m³K]	heat capacity of the wet material
$dw/d\varphi$	[kg/m³]	humidity capacity of the wet material
λ	[W/mK]	thermal conductivity of the wet material
D_φ	[kg/ms]	fluid/ liquid conduction coefficient
δ_p	[kg/msPa]	water vapour permeability of the material
h_V	[J/kg]	evaporation enthalpy
p_{sat}	[Pa]	water vapour saturation pressure
ϑ	[°C]	temperature
φ	[-]	relative humidity

WUFI Pro is used as simulation engine to model surface temperature of bricks for both wet and dry scenarios. WUFI uses the necessary hygro-thermal differential equations and delivers the needed output parameters as surface temperature (°C) and the water content within the construction. WUFI Pro is able to simule every detailed construction component specifically. The material of the brick with the greatest potential to be observed in the measurement was chosen for the simulation. A red unsealed brick type "Bologna" was used, which has the best suction characteristics compared to the other measured bricks. The measured brick is modelled as a single, one-dimensional material layer, consisting of 115 mm thick brick elements (λ=0.68 W/mK; μ=5.00; ρ=1.600 kg/m^3; c¬p=1.00 kJ/kgK; water suction capacity: 6.4 vol.%). For reasons of comparison, the same measured weather data are used from the nearby weather station TUM, located next to the testing area as an input. These measured data were hourly interpolated, because WUFI just imports hourly weather data. A south orientation was chosen for the simulation and the resolution of the time steps set to 30 minutes, to compare it with the measured data. For boundary conditions the measured initial surface temperatures of the bricks were used. The initial relative humidity for the dry brick was set up to 45% and for the wet brick to 96.5%, according to its measured initial weight.

Soaking the bricks overnight mainly reduces the initial temperature. Another approach for minimizing temperature peaks in summer is to irrigate the brick surfaces with the help of a targeted control signals using local weather dependent parameters. The outside air temperatures (threshold >20 °C, >25 °C, >30 °C) and the global radiation (threshold >400 W/m^2, >500 W/m^2, >600 W/m^2) were used as the control signal for irrigation. As a result, 30 different variants depending on the amount of water (4 L/m^{2}h, 5 L/m^{2}h, 6 L/m^{2}h) were simulated with WUFI and lead to differing irrigation frequencies. For comparing these simulation variants, average temperature difference for the whole year and for summer period (3.300 – 6.500 h) during the day and the maximum temperature difference were chosen as output values.

4 RESULTS

4.1 RESULTS OF IN-SITU MEASUREMENTS

As mentioned before for the discussion part red unsealed brick type "Bologna" is selected as an example due to better suction performance compared to the other brick types. The results of experiment shows that soaked bricks can decrease surface temperature significantly by daily average of about 7 °C. However, the color of the bricks is also influencing the temperature curve. Between the white and the black brick there was an average temperature difference of 5.4 °C. Fig. 7 illustrates the measured surface temperatures on the second day for dry and wet bricks.

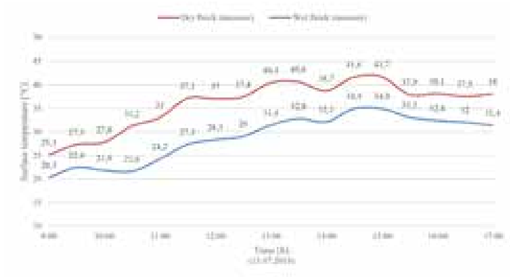

FIG. 7 Results of in-situ measurements second day for brick type Bologna

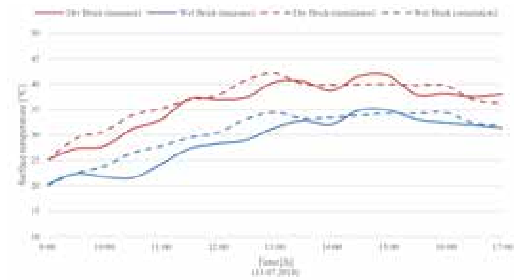

FIG. 8 Comparison measure results vs. simulation results

4.2 RESULTS OF NUMERICAL SIMULATIONS

The first part of the results compares the measures of the experiment with those of the WUFI simulation. The results are still different, as the time step had to be reduced to 30 min with the interpolated weather data and the water suction properties of bricks cannot be depicted more precisely for this transient hygro-thermal calculation method. The potential of the average temperature difference of 7.09 K (measure) was proved by the average temperature difference of the simulation (6.37 K). A more precise validation of the simulation results is not possible due to the limits of the existing simulation approaches and software tools and the limits of measurements under practical (not laboratory) conditions.

For the second part of the simulation, the yearly results of the irrigation of the brick wall in Madrid (Spain) are shown in Tab. 2 and Tab. 3. The results of the simulation are shown on the average year and the average summer hours, as well as maximum temperature difference values.

THRESHOLD TEMPERATURE [°C]	20	25	30	30	30
Threshold global Radiation [W/m²]	400	400	400	500	600
Irrigation frequency [h/a]	3151	2361	2032	1565	1249
Maximum temperature difference [K]	15.11	14.27	13.72	13.50	13.47
Average temperature difference (summer, daytime) [K]	5.83	4.95	4.56	4.3	3.4

TABLE 1 Influence of different threshold temperatures and global radiation for the irrigation control on the temperature difference of the dry and wet bricks (boundary conditions irrigation intensity 4 L/m²h)

The simulation results in Tab. 2 show the influence of different control variants depending on different parameters of the threshold temperature and threshold global radiation. The goal was to minimize the amount of water (represented by the irrigation frequency) used for the irrigation and to reach still rewarding temperature differences between the dry brick wall and the irrigated brick wall.

IRRIGATION INTENSITY [L/M²H]	4	5	6	7
Irrigation frequency [h/a]	1249	1249	1249	1249
Maximum temperature difference [K]	13.47	14.08	15.45	16.18
Average temperature difference (summer, daytime) [K]	3.4	4.56	5.04	5.46

TABLE 2 Influence of different threshold temperatures and global radiation for the irrigation control on the temperature difference of the dry and wet bricks (boundary conditions: Threshold temperature 30°C, Threshold global radiation 600 W/m²)

In a second step (Tab. 3), the irrigation intensity was increased from 4 L/m²h to 7 L/m²h while the irrigation frequency doesn't change due to the same boundary conditions of temperature and global radiation thresholds. The effect is that temperature differences increase significantly.

5 DISCUSSION

The in-situ measurements show a significant potential for evaporative cooling effects of irrigated brick façades. However, the effect of soaking bricks in their entire mass shows no advantage in comparison to surface watering of bricks. Especially in dry climate zones where use of water needs to be regulated, an optimized surface watering in specific times can significantly contribute to improved microclimate.

In order to ensure a watered surface of urban brick façades, an irrigation system of pipes distributing collected and filtered rainwater of the rooftop is proposed. Based on weather data, water is circulated through the pipes providing punctual irrigation of brick façades. Addressing a constructive approach, different façade typologies are classified. Basically, two application scenarios could be demonstrated: Retrofit application for existing buildings and Façade construction with irrigation system and optimized design. For new buildings, a unitized cladding system containing an optimized geometry of the bricks could be implemented as a first design strategy.

6 CONCLUSIONS

The potential of watered bricks decreasing surface temperature of building envelopes can significantly contribute to an improved microclimate and better thermal comfort. An average decrease of about 7°C due to evaporative cooling alone and the use of brighter colors of the bricks can also strongly influence the temperature curve, which is shown by the temperature difference of 5.4 °C between white and black bricks seen in the first experiment. Therefore, it can be assumed that both characteristics (water absorption capacity of bricks that enables evaporative cooling and color) can reduce the surface temperature of bricks even greater when combined together and could contribute towards a positive impact on micro-climate. Based on the measurements and simulations, a constructive experiment setup needs to be build and evaluated on a larger scale. The experiment setup needs to contain the integrated pipework for irrigation as well as a control strategy based on weather data to allow an efficient use of water in dry and hot climate zones.

Acknowledgements

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Façades: Past, Present and Future – Marking 50 Years of Continuous Development

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7 QUALICOAT, Zurich, Switzerland

Abstract
To mark the 50th year of FAECF, the European Federation of the National Window and Curtain Walling Manufacturers' Associations, this paper looks back at the development of the façade, with a focus on curtain walling and asks: "Is there anything new under the sun?" While on the face of it, the building skin has performed the same functions for the last 50 years and beyond, we show that it is the detailing and implementation of the building envelope, along with our ability to integrate energy efficiency, occupant comfort and sustainability, with the aid of computer modelling, modern manufacturing techniques and improved materials, that sets the modern façade apart from those in the past. As we look to the next 50 years, we can only expect innovation to accelerate. We can anticipate greater control of the indoor environment, and more intelligent structures: structures that can share data and sense and adapt to the external conditions and occupant requirements. We will also see an increased emphasis on the circular economy and the use of robotics for manufacture and installation, presenting opportunities and threats for our members.

Keywords
aluminium, curtain walling, occupant comfort, occupant wellbeing, biophilic design, material sustainability, circular economy, durability, flexibility, digitalisation

1 INTRODUCTION

FAECF, la Fédération des Associations Européennes des Constructeurs de Fenêtres et de Façades (the European Federation of the National Window and Curtain Walling Manufacturers' Associations), was founded in 1968 and celebrates fifty years of operation in 2018. The main objective of FAECF is to promote and defend the European fenestration industry in its chosen markets. It contributes to harmonization in fenestration standards and provides technical information to the industry.

During a moment of reflection, we wondered what was happening in the world of building façades up to 1968 when FAECF was founded. How have façades developed since 1968 up to the present day? What trends will we see emerge in the next fifty years? To try to address these questions, this paper will focus on one framing material, without which our federation would not be possible: aluminium. As the one of the pioneers of modernist architecture Ludwig Mies van der Rohe (1886-1969) put it: "The danger with aluminium is that you can do whatever you like with it; it doesn't really have any limitations." We will also focus on one façade system: curtain walling.

FIG. 1 The London skyline featuring The Shard *(source: Shutterstock.com)*

Some twenty years before the founding of FAECF, James Marston Fitch (Fitch, 1948) described the building envelope as a two-way filter – "a selective, permeable membrane". Fitch saw the building envelope as analogous to our skin, which helps our body respond to the external environment and maintain optimal operating conditions. Few of us can live in climates that allow us to be exposed to the elements all year round; usually we need clothes and we need buildings to act as the two-way interface between us and the external environment, as Fitch also concluded. From the groundbreaking curved forms of the Barcelona Trade buildings completed in 1968, to the iconic Shard standing at 309.7 m and completed in 2012 (see Fig. 1), curtain walling has provided architects with creative, flexible and sustainable solutions to their increasingly complex designs and growing end-user requirements.

In the following sections, this paper explores the development of curtain walling as our second "skin" in the following contexts: as a selective filter with respect to occupant comfort and wellbeing, material sustainability, and digitalisation.

2 COMFORT AND WELLBEING

Since we emerged from caves and started to build homes, we have understood that buildings should protect us from extreme outdoor conditions, as well as from woolly mammoths. In Northern Europe the focus was perhaps on the need for insulation in the building envelope. But does this mean we need to go back to the caves, with thick walls and no windows? Of course not, architects increasingly recognise that façades must be designed to provide comfort by using the right materials and the energy balance concept. Educating and empowering homeowners with similar knowledge when selecting their windows, is an important campaign message for FAECF: tailored advice is important to reflect the local climate as well as the size and orientation of the windows.

2.1 THERMAL COMFORT

To provide good thermal conditions, which are not solely about room temperature, energy efficiency is achieved with glazing by maximising solar gains in the heating season while minimising heat losses; in the cooling season solar gains need to be reduced with appropriate shading. Hence, important parameters that affect the energy balance include the area of glazing, its orientation relative to the sun and the local climate (European Aluminium, n.d.). With its high strength to weight ratio, aluminium has long been used to frame glazing and maximise the transparent area. This also provides more daylighting and opportunities for natural ventilation, also important factors for building occupant wellbeing. As Winston Churchill put it when referring to the rebuilding of the UK Parliament Chamber (UK Parliament, n.d.): "We shape our buildings, and afterwards our building shape us".

As noted in a literature review (Poirazis, 2004), double skin façades can provide both improved indoor climate and reduced energy at the same time – if designed properly. Although the concept of double skin façades is not new, and there are many different definitions and implementations of this envelope system, there is increasing interest in this type of construction, particularly in Europe. Harrison and Meyer-Boake (Harrison & Meyer-Boake, 2003) described the double skin façade system as: "Essentially a pair of glass 'skins' separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound. Sun-shading devices are often located between the two skins."

As recorded by Poirazis (Poirazis, 2004), Saelens (Saelens, 2002) mentions that: "In 1849, Jean-Baptiste Jobard ... described an early version of a mechanically ventilated multiple skin façade. He mentions how in winter hot air should be circulated between two glazings, while in summer it should be cold air." Crespo (Crespo) claims that the first instance of a double skin curtain wall appears in 1903 in the Steiff Factory in Giengen, Germany. Here the priorities were: "To maximise daylighting while taking into account the cold weather and strong winds of the region. The building was a success and two additions were built in 1904 and 1908 with the same double skin system ... All buildings are still in use." Arguably, this structure was the first example of curtain walling, outside of shopfronts and wintergardens.

Bringing this topic up to date, Crespo (Crespo) also notes that: "In the 90's two factors strongly influenced the proliferation of double skin façades…increasing environmental concerns start influencing architectural design both from a technical standpoint but also as a political influence that makes "green buildings" a good image for corporate architecture." Nevertheless, as noted in a 2005 report into the state of the art for double skin façades (Streicher, 2005), an advanced façade should allow for a comfortable indoor climate, sound protection and good lighting, while minimising the demand for auxiliary energy input. Double skin façades have the potential to offer solutions for this conundrum.

Examples of double skin façades can be found in several European countries. One Angel Square in Manchester, UK, is the Co-operative Group's new headquarters building, where more than 3,000 Co-op employees are co-located in one office for the first time. The Co-op is a consumer co-operative, owned by millions of members and the UK's fifth biggest food retailer. The 15-storey building is a three-sided structure, designed by architects 3DReid, with a fully glazed double skin façade that curves both horizontally and vertically around the building (see Fig. 2). It was awarded the BREEAM rating 'Outstanding'. The double skin façade along with the atrium structure used here are key to creating natural heating, cooling and lighting. In summer louvres at the top of the façade open to allow the warmed air trapped between its inner and outer skins to rise up and out of the building. In winter these louvres close so the façade can form an insulating blanket around the building.

FIG. 2 Construction of the double skin façade at One Angel Square, Manchester, UK *(source: Alastair Wallace / Shutterstock.com)*

2.2 DAYLIGHTING AND INDOOR AIR QUALITY

With the relationships noted above, there is a need to integrate thermal comfort, natural ventilation and daylighting strategies. Research has shown that typical business operating costs can be broken down into 1% energy costs, 9% rental costs and 90% staff costs (Browning, 2012). Therefore, anything that impacts the ability of employees to be productive should be a major concern for any organisation. Good lighting is critical for occupant wellbeing, which is closely connected to views of the outside world.

As highlighted in a review of best practice for "green" offices (World Green Building Council, 2015), research in 2003 identified 15 studies linking improved ventilation with up to 11% gains in productivity, because of increased outside air rates, dedicated delivery of fresh air to the workstation and reduced levels of pollutants (Loftness, Hartkopf, & Gurtekin, 2003). As the same review noted, it is a challenge to ventilate and cool offices in warm climates without a massive increase in energy use, but through innovative façade design and more energy efficient passive systems, natural ventilation must be an integral part of any solution.

2.3 BIOPHILIC DESIGN

Linked to the above issues, there is a growing (no pun intended) scientific understanding of biophilic design, and the positive impact of green space and nature on mental health. While climbing plants such as creepers and roses have been seen growing on house walls for decades, not always intentionally and sometimes to the detriment of the structure it must be said, the green façade is an emerging trend that is quite literally taking the window box to the next level.

Bosco Verticale (Vertical Forest) is a pair of residential tower blocks in Milan, designed by Boeri Studio and completed in 2014 (Fig. 3). Here the façade has been designed to incorporate over 700 trees and numerous plants and shrubs, reckoned to be the equivalent of one hectare of typical woodland.

FIG. 3 Bosco Verticale with the UniCredit Tower behind in Milan, Italy. *(Source: Konstantin Tronin / Shutterstock.com)*

3 MATERIAL SUSTAINABILITY

Buildings must be able to demonstrate their sustainability credentials and the façade has an important role to play in this. It is important to assess the façade in a holistic sense, as part of the whole building: from design, manufacture, in use and at end-of-life. This approach is usually captured through Life Cycle Analysis (LCA). Sustainable building assessment schemes such as BREEAM, LEED and DGNB have helped in raising awareness of the issues, despite not always fully reflecting the value of metals at end-of-life. Typically, the façade represents 10-15% of the total score available to a building in a given assessment scheme. As our own skin is essential for life, so the façade of a building is also indispensable. Without a façade with up to date functionality, it is impossible for the building to meet the latest sustainability criteria. Which also means façades should be able to adapt to the changing needs of society, to remain truly sustainable. While there are many definitions for "sustainability", in the context of the façade we include energy efficiency, and we include the ability to sense and respond to external factors and user behaviour to control light and ventilation for occupant comfort, as discussed previously. In this section, we consider material sustainability, with a focus on aluminium, i.e. how long it lasts and what happens at the end-of-life.

3.1 DURABILITY AND FLEXIBILITY

Although in relative terms, aluminium is a "new" metal, with affordable volume production of aluminium invented by Charles Martin Hall and Paul Héroult in 1886, its durability credentials are well established. The Pavillon du Centenaire de l'Aluminium was designed by Jean Prouvé (1901-1984), celebrating 100 years from the first production of aluminium in France in 1854 using the method developed by Henri Étienne Sainte-Claire Deville. It was built in Paris in 1954 using an aluminium framework with aluminium panels and glass infills (see Fig. 4). The building was considered a landmark in 20th century architecture and it further demonstrated the potential for aluminium to create buildings made of lightweight prefabricated structures with pure simple lines. It was first rebuilt in Lille in 1956 and subsequently renovated and rebuilt in 2001 at the Parc des Expositions, Villepinte, Paris, demonstrating not only the durability of aluminium structures, but also their inherent flexibility.

FIG. 4 Pavillon du Centenaire de l'Aluminium, designed by Jean Prouvé *(Source: Ben Fisher of Michael Stacey Architects, see (Stacey, 2014))*

In 1934, anodised aluminium windows were installed at the University of Cambridge Library; they are still in good working order today. In 1953, described by Popular Mechanics as 'the world's first aluminium skyscraper', the Alcoa Building in Pittsburgh, Pennsylvania, USA, was clad in "unitised" pressed aluminium curtain walling. When visually inspected in 2013, this project is described as in remarkably good condition (Stacey, 2014).

As part of their interim conclusion from extensive research into the use of aluminium in the façade, Stacey et al (Stacey, 2014) noted critical factors for durability, including alloy composition, surface finish and regular cleaning: "The interim conclusion of this research suggests that well-specified and well-detailed aluminium architecture should be considered to be very durable and have a very long life expectancy. The oldest extant aluminium components of architecture in this study are now 120 years old." We are often asked what the service life of aluminium windows is. Third parties such as the Building Research Establishment in the UK give a reference service life for aluminium windows of 40 years. Based on their findings, Stacey et al recommend that this is revised to at least 80 years based on the frame material, intermediate replacements of weather stripping and Insulating Glass Units notwithstanding.

It is worth noting that several office buildings designed and constructed in the 1970s and 80s in Europe, such as Tour First, have now been renovated. Renewal of the façade to improve energy efficiency and occupant wellbeing, while maintaining the buildings' outer appearance, is usually an important aspect of this renovation. Replacement of outdated and inefficient IGUs with modern coated glass systems alongside computer-controlled solar shading and ventilation systems tailored to each building, for example, increases operational efficiency and improves comfort for building occupants (Hannoudi, Christensen, & Lauring, 2015) (Fotopoulou, Semprini, Cattani, Schihin, & Weyer, 2018). The flexibility of curtain walling systems facilitates such renovation and means that buildings can be improved cost-effectively and sustainably, although this should always be assessed through LCA. Another key role for FAECF is to promote this message and find ways to increase the rates of building renovation in Europe.

3.2 CIRCULAR ECONOMY

The concept of the circular economy has arisen from consideration of material flows and the need to maintain access to those materials and resources for future use. For a truly circular materials flow, there is a need to maintain, refurbish, reuse and recycle products at end-of-life, feeding the components and materials back into the lifecycle of the original product in a closed loop. With their durable nature, reusability and excellent recyclability, metals lend themselves to the circular economy.

While consideration of the circular economy has tended to focus on products such as fast-moving consumer goods and relatively short-lived electronic goods to date, policy makers are seeking to address the circular economy in construction, where the time between product manufacture and their end-of-("first")-life can be relatively long. By weight however, construction and demolition waste is the single biggest waste stream in the EU, and this must be addressed (Reike, Vermeulen, & Witjes, 2018).

In a construction context, the circular economy is focused on maximising the reusability and recycling of products and raw materials at the end of a building's life, minimising the loss of valuable materials while also fully contributing to the design. This is far removed from the linear "take-make-consume-dispose" model, in which raw materials are converted into products that are effectively lost at the end of their life cycle.

Metals are almost infinitely recyclable and while high economic value is the main driver for systematic collection and recycling of aluminium building products at end-of-life, with more than 95% of aluminium products used in buildings collected, there is considerable current interest in developing closed loop recycling schemes for aluminium building products in Europe, following the A|U|F scheme currently operating in Germany (A|U|F, n.d.). Such a closed loop scheme allows for closer control of the composition of the recycled material, with a high-quality window, door or curtain walling profile recycled into another high-quality window, door or curtain walling profile. As shown by the international organisation European Aluminium in detail for aluminium window frame recycling, recent advances in analysis and separation technologies allow for new recycling routes that can be applied in different markets.

FIG. 5 Paviljoen ABN AMRO in Amsterdam *(Photo courtesy: De Groot & Visser)*

The Dutch bank ABN AMRO supports the transition to the circular economy and is keen to set an example when it comes to its own offices. The ABM AMRO Circl Pavilion (VMRG, n.d.) (Circl, n.d.), designed by Architekten Cie in 2015 and situated in front of the ABN AMRO headquarters in Amsterdam, claims to be the first circular building design in the Netherlands and has been nominated for the Dutch Architectural Association Best Building of the Year 2018 (see Fig. 5).

The project has involved a close partnership between architects, advisors, universities and suppliers of the next generation of sustainable solutions. BREEAM has been a driver for ABN AMRO. The expected energy use of the ABN AMRO Pavilion is 58 kWh per m^2 gross floor area (GFA) per year, with 65% of this energy coming from renewable sources. This is about half of the typical energy use for an office where around 20 people work. The expected water consumption per person per year is 5 m^3, with 40% coming from rainwater or grey water. With the Pavilion, ABN AMRO hopes to set a benchmark for circular buildings of the future. The Pavilion is a 'living lab' that can continuously adapt to changes in use and its environment and test new technology.

After a wide search, ABN AMRO ultimately chose a local company for the Pavilion's solar-panels, Exasun. Exasun designs and manufactures its panels in the Netherlands, thus reducing shipping costs and environmental impact. Moreover, Exasun produces panels that have glass layers on both their top and under-sides. This makes them more sustainable than standard panels, which lose around 0.7% of their output per annum. The Exasun panels are expected to last for a minimum of 50 years. There are 260 panels installed on the roof of the Pavilion, with a further 260 fitted all along the outer edge of the building's exterior walls.

Together with TU Delft, the building's designers came up with a number of energy-efficient systems, including the Pavilion's system of horizontal and vertical geothermal heat exchangers which help to reduce 'normal' energy usage. The vertical heat exchangers comprise a series of nine boreholes, some 80 metres deep, and use geothermal energy to heat and cool the building.

PCMs – Phase Change Materials – were used throughout the floor and ceilings in the ground floor. PCMs are similar to the elements in a cool box and contain a saline solution which either solidifies or melts depending on the temperature. They essentially work like a thermal battery. When a space reaches the desired temperature – 20°C, for example – the solution melts and produces a cooling effect. When the temperature drops – when thermally cooled water from the geothermal heat exchangers is pumped over the PCMs, for example –the solution solidifies and 'recharges' the phase-change 'battery'. A thermal buffer like this means the temperature in the building can be controlled with a minimum use of energy.

As well as trialling innovations such as PCMs and insulation material made from recycled jeans, the ABN AMRO Pavilion was designed as an open and transparent structure using extensive aluminium curtain walling in the façade that ensures excellent daylight levels in the building, as well as feelings of space and connection with the outside world. It should be noted that prefabricated elements designed to be more easily dismantled and recycled are often used in the construction of buildings that are based on the principles of circularity.

The curtain walling system used makes glass infill weights of up to 700 kg possible thanks to patented thermally-broken glass supports. This combined with the ability to accept glazing units up to 60 mm wide, means that triple glazing with low U-values can be used. The maximum glass weight of 700 kg also allows larger sizes of glass to be used for maximum transparency and an optimal incidence of natural light. The Uf value is 0.81 W/m2K.

4 DIGITALISATION AND BIM

Building Information Modelling (BIM) is a common theme of these initiatives. Of course, BIM is not a new concept. A paper in the 1980s predicted that model objects would connect to relational databases containing product data. Architects have long used software tools to design, plan and analyse buildings. While most have focused on the visual 3D aspects of modelling historically, the importance of data (the "I" of BIM) is rightly coming to the fore. BIM can be also traced to developments in the engineering world for the exchange of product data, including the Initial Graphics Exchange Specification (IGES) in the 1970s and 1980s, and ISO 10303, known informally as STEP (Standard for the Exchange of Product model data), in the 1990s. For the automotive and aerospace sectors, the benefits of such standards are clear and widely adopted.

Hence, there is an urgent need for recognised international standards for BIM, particularly with respect to construction product data. In 2018, two "foundation" European standards are scheduled to be published: EN ISO 19650-1 (Organization of information about construction works -- Information management using building information modelling -- Part 1: Concepts and principles) and EN ISO 19650-2 (Part 2: Delivery phase of the assets). This should be followed in 2020 by parts 3 (Operational phase of assets) and 5 (Specification for security-minded building information modelling, digital built environments and smart asset management). However, 2020 is also likely to be the earliest that any European standards for managing construction product data will be published.

There are several challenges for façade-related products with respect to product data. They are usually bespoke and built as an assembly, particularly in a commercial construction context, and their performance will depend on the design details as well as their interaction with the rest of the building. Any product data will therefore need to highlight this interdependency, and the supply chain will need to maintain and update the product data as each design develops. This is also closely linked with the "Smart CE marking" initiative. For SME fabricators and installers, this could require dedicated resource and a change in working practices.

Such a change should not be implemented by first adopting a software platform and changing business processes to suit. It has long been recognised that in any change programme, first address the "people", then the "process" and then finally the "technology"; the required data should be the result. Step one is changing the culture. Therefore, we need to continue explaining the benefits of BIM to all decision makers and ensure that each organisation that will need to implement BIM has its own "BIM Champion" in place now.

A'DAM Toren is the new name for 'Toren Overhoeks'. This Dutch tower was designed by the architect Arthur Staal as a commission by Royal Dutch Shell. It was first officially opened in 1971 and was home to the multinational oil company until 2009. Staal designed the office tower at 45° to the river IJ waterfront. This diagonal position ('overhoeks' in Dutch) gave the building its first name. In 2017 A'DAM finished an extensive three-year renovation programme and it has been transformed into an iconic multifunctional tower (VMRG, n.d.). It is now home to a mix of offices, cafés, restaurants, a hotel, an observation point and a revolving restaurant. The plinth and the crown of the building are made using curtain walling, with many unique features, including almost 800 concrete elements utilising specially developed aluminium frames and 18 m^2 windows weighing 1,850 kg each.

FIG. 6 A'DAM Toren, Amsterdam *(source: Evaldas Jankauskas / Shutterstock.com)*

A'DAM opened in May 2016 and is seen as a catalyst for the regeneration of the Overhoeks area (see Fig. 6). BIM was used extensively in the project, which allowed offsite manufacture of the glazed elements, comprising the aluminium inner frames inserted into the concrete outer frames. This effectively halved the number of lifting movements needed on site and the construction of the façade on site took only eight weeks.

4.1 OFFSITE MANUFACTURE AND MODULAR CONSTRUCTION

The current shortage of housing in parts of Europe, the digitalisation of construction and the circular economy are three of the factors helping to drive offsite manufacture and volumetric, modular construction. Arguably, for most window units and unitised curtain walling, our industry is already engaged in offsite manufacture, and to address the housing shortage in the UK in the 1940s, aluminium prefabricated housing was built using capacity from the aircraft industry factories. In total, 54,500 of these aluminium "prefabs" were manufactured. These modest detached houses proved very popular and although their planned life was only up to ten years a small number still survives. So these concepts may not be new to us.

While a car is precision engineered from modules by robots in a clean factory, we typically assemble new buildings in a muddy field (at least, this is usual in the UK). However, things will now change for the better. When the Holiday Inn Express in Manchester, UK, was recently constructed, 220 bedrooms were essentially assembled onsite in four weeks from completed modules based on shipping containers. Overall, it is reckoned by the designers Chapman Taylor that the modular build saved nearly six months from the build time, when compared with traditional methods. In terms of the value chain interactions, offsite and modular construction methods are no different from traditional methods in many respects. For example, the specialist façade contractor should be engaged from the start of the process to ensure that their expertise and input is joined up with other professions.

Unitised curtain walling could also be considered as a type of offsite manufacture, and current designs are considerably more sophisticated than early versions from 50 years ago. Increased control of quality, greater levels of airtightness and weather resistance and the need to overcome limitations with site access are some of the factors fuelling the growth in the use of unitised systems in some markets.

4.2 DEVELOPMENTS ONSITE

The use of robots in the construction industry is forecast to grow considerably over the next five years. Valued at $76.6m in 2018, the construction robot market is predicted to more than double in size to $166m by 2023, growing at around 17% a year (MarketsandMarkets, 2018). Growth will be mainly driven by factors such as demand for enhanced productivity, quality, and safety due to growing urbanisation worldwide. Labour shortages are predicted to lead to the rise of exoskeletal robots over the next five years, with this particular market segment expected to grow the most between now and 2023. Europe is seen as a major territory for construction robots. This is attributed to the large facilities of various companies for the development and production of construction and demolition robots, increasing number of government regulations, and growing need for residential and non-residential construction projects.

While high equipment costs inhibit market growth in construction robots, factors such as the adoption of 3D printing for construction and a general rise in automation at construction sites could help to open the market. Similar growth rates are predicted for the use of drones in construction. Whether this goes beyond tasks such as imaging and surveying of construction sites, to heavy lifting, for example, remains to be seen.

5 ANALYSIS

It is difficult in a single paper to encapsulate all the developments in façades and curtain walling throughout history, as well as look into the future, and we acknowledge that we will have missed some important aspects and that our selection of case studies is subjective. In this paper we focused our attention on Europe, and we recognise that innovation is not restricted to these shores. The timeline in Fig. 7 below includes the buildings featured in this paper. It has been observed that 1955 to 1980 was a key period in the development of aluminium curtain-walling systems in Europe and in the USA (Stacey, 2014), and certainly in Europe we continue to push the boundaries of what is possible in curtain walling design, as we respond to changes in society. As Fitch observed back in 1948 (Fitch, 1948), the external walls of buildings have always acted as selective permeable membranes, but modern scientific knowledge and technical competence merely make possible much higher, more elegant and precise levels of performance than previously.

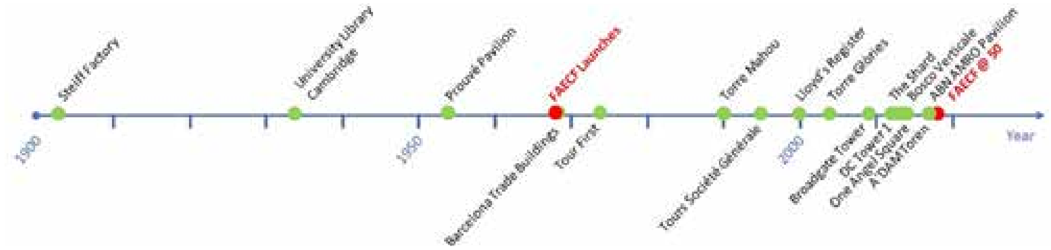

FIG. 7 Timeline highlighting the completion dates for selected landmark buildings, including those featured in this paper

6 CONCLUSIONS

Many concerns and concepts that we have focused on in this paper, are not new in the 21st century, such as double skin façades, offsite manufacture and prefabrication, it is the detailing and implementation of these techniques, and our ability to combine them with energy efficiency, occupant comfort and sustainability, with the aid of computer models, modern manufacturing techniques and improved materials, that sets the modern façade apart from those in the past. We will also expect greater control of the indoor environment, and more intelligent structures: structures that can share data and sense and adapt to the external conditions and occupant requirements. Just as a smartphone does not contain any new technology per se, as the camera, the radio, the web browser, the satnav and (yes they do come with one) the phone itself are not new inventions; it is how the technologies are combined and applied that has made the smartphone ubiquitous. It will be the same with façades, where the challenge will be to combine all the competing requirements of the external façade into one coherent solution.

While the use of data must be carefully controlled, not least to protect the privacy of the individual and to avoid sensitive data getting into the wrong hands, data will become increasingly important to the façade sector. Performance data from a building will not only be critical in optimising the performance of the façade but also in learning lessons and improving the next project. With the façade moving from a product to more of a service, the relationships in the value chain are changing, with the façade contractor increasingly becoming a long-term partner. Disciplines that were perhaps not routinely considered part of the façade contractor's role in the 1960's will be integral in the future: computer-aided design and manufacture including BIM; new financial and contracting models; as-built and end-user data analysis; integrated maintenance, disassembly and remanufacturing functions.

The members of the national and internationl Associations that are part of FAECF have successfully adapted to the changing face of the sector since 1968; with the continuing support of FAECF, our members will meet the challenges from the next 50 years.

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Novel Technologies to Assure As-Designed Solutions for Energy-Efficient Refurbishment Scenarios

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Abstract

Combined with growing expectations for high performance, Energy-efficient buildings (EeB) are now required to satisfy a large number of parameters, both in case of new built and in deep renovation projects. The main goal of the INSITER project is to improve building energy efficiency in the sector of new construction and refurbishment, by developing self-instruction and self-inspection procedures, supported by BIM-based software tools, Augmented Reality applications and measurement tools that shall be integrated in a software-based platform. The 8-step methodology, presented in the paper, is the bridge to bring research knowledge into practical implementation saving time and costs by making the construction efficient, and its applicability is demonstrated through on-site application. In particular, a case study of an existing educational facility is described in detail: the field activities are mainly related to the methodologies and technologies for the investigation and mapping stage, developed by the INSITER project with the aim to evaluate the geometric features and thermal performance of the building envelope and provide reliable findings that are the basis for the development of refurbishment scenarios.

Keywords

energy efficiency, self-inspection, quality control, performance assessment, BIM, Augmented Reality

1 INTRODUCTION

The construction sector is responsible for almost 40% of energy consumption and 36% of CO2 emissions in the European Union (European commission, 2014), while at the same time 2050 low-carbon economy roadmap aspires to up to 90% emission cuts from the building stock. The European policy framework aims at creating the conditions to improve energy efficiency of new and existing buildings. To this end a major step forward is represented by the Energy Performance of Buildings Directive (EPBD, Directive 2002/91/EC), and its recast (EPBD recast, Directive 2010/31/EC) that states the implementation of nearly zero energy buildings (NZEBs) as the building target from 2018 onwards (D'Agostino et al., 2017).

However, recent findings by the Chartered Institution of Building Services Engineers (CIBSE) show that buildings typically consume two times more energy than predicted at the design stage (Menezes, 2012). This way, realising the targeted performance in design is hampered by critical shortcomings during on-site construction and refurbishment that cause a lower built-quality and sub-optimal energy savings in the building lifecycle. Evidence of the energy performance gap for new or retrofitted buildings is presented in the literature since the end of the 1990s, when Haas et al. (Haas et al., 1998) identified a gap between predicted (expected) and observed energy performances of buildings (Cali et al., 2016). The energy efficiency of buildings is closely linked also to the construction quality.

The construction sector demonstrate that industrialization and digitization have become more and more common in the European building market. Modern buildings are largely made of prefabricated products whose design and technical performance has been tested prior to on-site assembly defining in detail the energy performance of prefab buildings. This trend is valorised in consideration that the critical mass of Energy-efficient Buildings (EeB) in Europe by 2020 will be achieved through sustainable industrialisation of high-performance architectural, structural and building-service components. Therefore, the advance on completion of new and refurbishment solutions for critical building components, in new and existing facilities, can have important effects. In fact, critical components to energy efficiency have indeed proven to have significant impact for new and refurbishment buildings.

Nowadays, one of the main issues is that the as-design solutions for EeBs are often not properly implemented on site. Such discrepancies are caused by, on one side, misunderstandings by construction worker about how design specifications and assembly manuals of prefab solutions should be implemented on site; and on the other side, lack of on-site practical considerations by designers and manufacturers when developing, producing and delivering the prefab solutions. Thus, a significant part of the building's performance gap is caused by lack of knowledge of the as-is situation: the procedures of inspection are mainly based on worker's experience and do not usually follow detailed protocols to obtain an assessment on the actual energy performance of the envelope, that are the basis to develop reliable and cost-effective refurbishment scenarios. As a result, the quality control processes are often at risk and the energy performance of the building may fail to achieve the required levels.

In this field, the main purpose of the INSITER project (Intuitive self-inspection techniques using Augmented Reality for construction, refurbishment and maintenance of energy-efficient buildings made of prefabricated components, funding from the European Union's Horizon 2020 research and innovation program under grant agreement n.636063) is to eliminate the gaps in quality and energy-performance between design and on-site condition in order to build or renovate energy-efficient buildings, through detecting and preventing quality and performance gaps between the mapping, design and construction of buildings mostly made of prefab components.

2 METHODOLOGY: THE INSITER PROJECT

The INSITER project lead by Demo Consultants is an international research project that involves 13 partners from six different EU countries (Netherlands, Italy, Germany, Bulgaria, Spain and Belgium) that runs from November 2014 till end 2018. The research activity is proposed on buildings based on prefabricated components, organizing the work in seven work-packages (WP):

- WP1 dedicated to Self-inspection techniques and process methodologies;
- WP2 dedicated to Portable and robust systems and equipment for self-inspection;
- WP3 dedicated to User-friendly software applications for self-inspection;
- WP4 dedicated to BIM for self-inspection and self- instruction;
- WP5 dedicated to Validated solutions for closing the quality and performance gaps;
- WP6 dedicated to Training, communication, dissemination and exploitation;
- WP7 dedicated to Project management.

In order to meet the above-mentioned objective, the INSITER project proposed:

- Self-Inspection methods, for construction workers, experts and supervisors in order to map and detect construction errors;
- Self-Instruction methods, for construction workers in order to prevent construction errors.

These methods are supported by BIM-based software tools, Augmented Reality and 3D measurement instruments. Following this approach, the project has developed:

- practical guiding principles for the application of INSITER self-instruction and self-inspection methods, in order to meet the project goals and obtain an increase in the level of quality and energy efficiency on site. In other words, the "INSITER Guidelines" are the synthesis of the knowledge developed in INSITER, and the bridge to bring research knowledge into practical implementation;
- principles of application and implementation of practical contents to realize the "8-Step INSITER methodolo-gy" referring to demonstration cases concerning the energy-efficient critical components (building and MEP-HVAC) that most influence the energy performance.

INSITER has developed an 8-step methodology, that was the basis to perform the demonstration activities and to develop a dedicated App for construction/refurbishment stage (see picture 1 below).

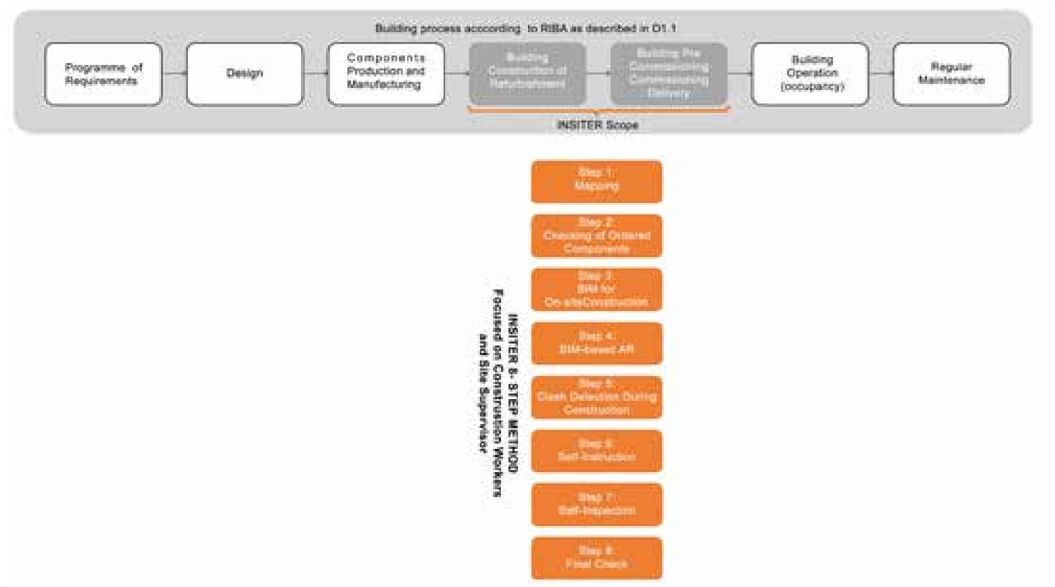

FIG. 1 INSITER focus is related to the building inspection "on-site" during the building construction.

The concept of self-inspection that is performed simultaneously with on-site processes has a strong contrast with the traditional post-inspection approach. In fact, in order to solve real problems during construction, refurbishment, maintenance and commissioning, INSITER developed a new methodology for self-inspection with a dedicated toolset.

2.1 CRITICAL BUILDING COMPONENTS AND MAIN BUILDING ENVELOPE CONSTRUCTION ERRORS

The main aim of the research is to develop analytical and quantifiable methods that will contribute to building defect inspection manuals, respectively for new construction and refurbishment, in order to avoid or at least reduce installation errors that cause a gap not only in terms of energy performance but also in terms of realization costs and construction time schedule. As a starting point, the focus has been to assess which are the building elements that can be recognized as "critical" to achieve the as-designed performance criteria: in fact, the first step of the research project consisted in the identification of relevant building envelope and MEP/HVAC systems and sub-systems that affect the whole energy performance, including in depth analysis of tools and methods relevant for inspection of these components as per current practices. In particular, the building envelope has been divided into five groups, each with their own characteristics. Following the workflow of the construction process, all elements of the building envelope that affect energy and quality have been identified, and the classification has been made as follows:

- Foundation and ground floor, including foundation connection and façade connection;
- Solid prefab façades, including window openings (façade – frame);
- Glass façades (curtain walls);
- Roofing systems, flat or pitched;
- Connections between existing building and new elements.

A parallel analysis has been performed considering the main technical systems. Four main MEP systems have been selected, together covering for over 90% of all systems with a relation to indoor environment and energy usage:

- Heating & cooling (with heat pump);
- Mechanical ventilation (with heat recovery);
- Solar hot water;
- LED lighting.

The second step has implied the analysis of the main construction errors and failures that more often occur on site. The list of errors and including a description of each error has been presented and the assembly process has been outlined for each building component, including maintenance and service life phase. After that, the main construction failures affecting the selected building element have been analysed in detail in order to map the main problems and identify at which stage of the workflow they occur.

For each critical EEB component, the relevant KPIs and parameters have been elaborated, and related conceptual techniques have been proposed to perform self-inspection during the building construction process. This part of the research has also analysed the process framework, and identified two main stages in which the choice of building components is critical for Energy Performance and therefore when KPIs, with related parameters, need to be meas-ured:

- Construction and assembly processes are now part of the critical path to reach the final energy performance. Any defect can lead to disorders and even pathologies which hamper the durability of the building performance;
- Performance assessment (for existing buildings) enables users/owners/investors to oversee and control energy consumption and behaviour, allows detecting potential misuses of buildings due to a lack of awareness of the users, potential disorders and/or pathologies of the monitored building.

INSITER focus intended to derive from these analyses some general concepts to be applied to the different cases. The generalization, according to a deductive process, was an essential element in the research to develop a common knowledge platform aimed at limiting the discretionality of judgment during the construction works and thus to provide immediate and reliable feedback, not only based on the skill and experience of who is performing the installation or the inspection. These results, which were briefly outlined above, have represented the basis for developing the INSITER methodology at both the procedural and content level.

2.2 THE INSITER GUIDELINES

After a preliminary critical review process, the INSITER project proposed a new 8-step self-inspection methodology. The self-inspection methodology of INSITER will not disrupt the working processes on site; on the contrary, it will save time and cost by making the processes more efficient and accurate. The INSITER methodology is based on eight steps and provides for integration with BIM models and AR techniques, as summarized below step-by-step:

Step 1

Mapping actual technical conditions of the site and building, and performing an economic assessment of the property and land; capture the requirements and compare them to as-is situation. This step is performed by the construction workers after receiving the work assignment. The workers check whether the working areas (e.g. construction site designated for a new building or a storey in an existing building) are cleared and ready for the planned construction/refurbishment activities. In case of refurbishment of existing HVAC/MEP systems, “mapping” also means assessing the condition of the existing systems. Health and safety regulations are also addressed, for instance: the building site must be cleared of asbestos and the working areas must be safe/secured. Actual conditions (e.g. weather, accessibility, construction equipment, transport and logistic processes on-site) related to the planned works are also verified. The outcome of this mapping is used to verify the construction/ refurbishment work planning.

Step 2

Self-inspection at procurement, production and delivery of prefab components. This step is dedicated: 1) to check the correctness and conditions of the delivered prefab components, also validating delivery schedules compared to logistic planning; 2) to connect the 3D product databases from manufacturers and the positions of the components in the BIM model. In the case that pre-assembly is done in the factory, checking also means pre-delivery product inspection. Tests on the quality conformity of the delivered prefab components are performed, including integration of Non-Destructive Testing (NDT) methods as necessary.

Step 3

Modelling of the (existing) building, site and surroundings in Building Information Model (BIM). When a BIM model of the building does not exist, the existing building will be modelled in BIM, including detailed modelling of the current building and MEP/HVAC components that are critical for building quality and energy performance. BIM modelling will incorporate available 2D and 3D drawings and documentations of the building, as well as 3D laser scanning and point cloud data processing. Relevant GIS data will be included in BIM; information models of building/MEP components will be aggregated and converted to open-standard BIM. The BIM model can be viewed on mobile devices on the construction site.

Step 4

Generating and deploying BIM-based Augmented Reality (AR) for self-instruction and self-inspection. Two main actions are expected: 1) Embedding BIM and VR in Augmented Reality (AR), and extracting BIM / VR process information into 'self-instructions' (e.g. installation manuals and planning schedule) for construction workers on their mobile devices (e.g. iPad); and generating self-instruction modules. 2) Interfacing with data output from other inspection hardware (e.g. scanning, imaging and measurement equipment).

Step 5

Visual validation on-site based on the BIM clash detection performed prior to construction / refurbishment activities. BIM-based clash detection is performed before construction/ refurbishment. Clashes found should be resolved by the design/ engineering team, and the discoveries are recorded to be visualized in AR on-site. Review the clash details, and then determine the severity of the clash in several degrees (e.g. from 'easily fixed (human) error' to 'fundamental error requiring redesign'). If unresolved clashes are still found on-site, trace back the defaulting components, and request those involved to perform a review and to propose recovery solutions.

Step 6

Self-instruction during preparation and execution of construction site and logistics. This is one of the main innovative steps, and it is dedicated to help the construction workers in order to reduce construction errors. In detail the activities performed in this step are: 1) to check assembly manuals with support of BIM-based 3D visual instructions: 2) to implement 'self-instructions' on the mobile devices of the construction workers; 3) to provide supervision and support when needed; 5) to optimize time and cost schedules (also linked to production planning); 6) to analyse risks of delay and budget-overrun; and 7) to update the self-instruction guidelines for construction workers.

Step 7

Self-inspection during construction / refurbishment / maintenance process. The workers check the result and quality of the performed work on their own, according to online / digital check lists depending on the assembled components. When detailed inspections are needed, the related specialists will be called in. For instance, thermal performance air tightness, acoustics and humidity for building elements will be measured on the construction site by means of the procedures developed in INSITER: thermal and acoustic leakages will be identified using IR camera and Sound Brush allowing to visualise 3D pictures of the building acoustic and thermal field and calculate the sound insulation and the global U-value.

Step 8

Final check (Self-inspection and self-instruction during pre-commissioning, commissioning and project delivery). Comprehensive evaluation at certain intervals (e.g. weekly), performed by the site supervisor involving workers from contractors and sub-contractors. The preliminary quality and performance results are quantitatively measured and analysed as input for participatory decision-making. The project idea raised in consideration that more of 70% of all buildings in the EU nowadays are based on prefab components. Prefab architectural, structural, MEP and HVAC components currently are designed and manufactured according to high quality and performance standards. Despite this, the benefits of available energy-efficient building (EeB) components are lost by lack of knowledge or bad implementation during the construction processes. There is a gap between design and construction: the quality framework defined collectively at the design level is often not achieved during construction.

In order to simplify the application of the INSITER methodology, the consortium has proposed the "INSITER Guidelines" as practical guiding principles for applying the methodology. In other words, the "INSITER Guidelines" is the synthesis of the knowledge developed in INSITER, and the bridge to bring research knowledge into practical implementation (on-site). The guidelines are mainly developed for "construction workers" and "site supervisors" even if other players (experts, designer, building owner etc.) have a key role in order to create or collect the data and implement the complementary ICT solutions. The INSITER guidelines are digital and available through two main IT solutions elaborated in the research project and have been applied on real-world case studies: in fact, the final result is a quality assurance tool (mobile App with a user friendly interface, for BIM-based Augmented Reality, beta-version), applicable to different construction phases, that guides the construction worker through his daily on-site activities, while giving him indications and hints of mistakes to be avoided that could potentially lead to energy efficiency related shortcomings, and the

SharePoint platform (expert interface) that stores all data, including BIM models, pictures, database of components, checklists.

FIG. 2 INSITER mobile App for BIM-based Augmented Reality

3 CASE STUDIES AND REAL TESTS

The implementation of the INSITER methodology has been performed on six demonstration cases, that have involved building sites for new construction and refurbishment projects, prefab component factory and laboratories. For each case study, different use case scenarios have been carried out, based on the proposed INSITER methodology, in order to provide a wider overview and better proceed with the validation of INSITER procedures and measurement protocols.

One of the renovation projects involved the analysis of a prefabricated school building, located in the eastern portion of Pisa. The school complex "Concetto Marchesi" is an educational facility built in the 1970s with a modular construction system. The complex has a prefabricated concrete structure with pillars, beams and panels and consists of four different building portions, which house two different high schools, for approximately 14,612 m^2 and 43,836 m^3, and a total amount of approx. 1,675 students.

For the INSITER objectives, a complete investigation analysis has been performed, with on-site tests, laserscanning measurements and thermal tests. The activity was precisely that of tackling this project assignment using the methodology and measurement techniques developed by INSITER, with the aim of demonstrating how the INSITER methodologies allow to accelerate on-site operations and provide more reliable results for building assessment.

The two main problems that needed to be assessed throughout surveys and the investigations consisted of:

- Poor safety performance of the building envelope elements. In particular, liability of non-structural elements (prefab panels), that could collapse and cause injuries to the building occupants;

- Poor energy performance of the building envelope (prefab opaque panels, U-glasses of skylights, waterproofing layers), due to bad condition of building components.

3.1 USE CASE 1: CHECKING OF GEOMETRIC CONSISTENCY AND BIM VALIDATION

The first use case for the school complex in Pisa consisted in the check of the geometric consistency by performing a BIM acquisition and a deviation analysis of the model. This activity was aimed at verifying the safety performance of the building envelope elements, as per user's request.
The development of this use case involved the application of the INSITER methodology, in particular Step 1 – Mapping for existing building and Step 3 – Modelling of the existing building. The main scope was to assess the quality of as-is building performing the deviation analysis to evaluate the 3D models, which have been created on base of the available 2D drawings. The step has faced the increasing demand of acquire accurate Building Information Models (BIM) of existing building stock with the AEC sector. Therefore, this use case can be extended for a general procedure within the INSITER guidelines for mapping actual condition via Scan to BIM techniques. These as-built BIM's are often required to be modelled up to Level-of-detail (LOD) 300, and up to Level of Accuracy (LOA) 30. To provide this data, high resolution and high accuracy point cloud data was required. Data acquisition was performed using a terrestrial laser scanner type Leica ScanStation C10, along with total station measurements. Two major issues in the procedure have raised:

- Data occlusion: even with high resolution survey data, occluded zones like the interior of walls, floors and ceilings, cannot be avoided. However, a lot of occlusion is caused by the sensors position. Scan to BIM algorithms are forced to make assumptions about these zones, which often lead to misinterpretation. To minimize data occlusion, data coverage should be maximized, and thus, the sensor should be able to access all kinds of spaces;
  Resolution of the survey data: different zones and objects require a certain data resolution in order to be modelled correctly. However, with data resolution inversely proportional to the acquisition speed, the resolution/acquisition time ratio has to be optimized. Acquisition workflows should aim for maximizing speed with a minimum of misinterpretation.

Then, the type of point cloud influences Scan to BIM efficiency. Different survey systems provide varying types of point clouds. Reconstruction algorithms preferably work with structured data, for computational efficiency.

Terrestrial laser scanner has been selected for this use case: over the last decades, acquisition times have dropped from over half an hour to only a couple of minutes for each scan. This allows for more setups, resulting in larger data coverage. With data acquisition speeds up to a 1,000,000 HZ, weight down to 5-10kg, increased accuracies to up to 6mm/100m, terrestrial laser scanners look stronger than ever.

Some innovative and time-saving procedures have been introduced in the self-instructions:

- Eliminating scanner setup, tear-down, and powering off/on between stations saved five minutes per setup, resulting in a time reduction of 36 percent. With more than 400 setups, the net savings were significant;
- Using a wireless tablet with a larger display to control scanning, photo capture, and target acquisition provided high visibility for scan quality monitoring and better zooming resolution for critical aiming

at targets. In addition, operators were free to roam while scanning and were able to record targets with the tablet while walking to the next location.

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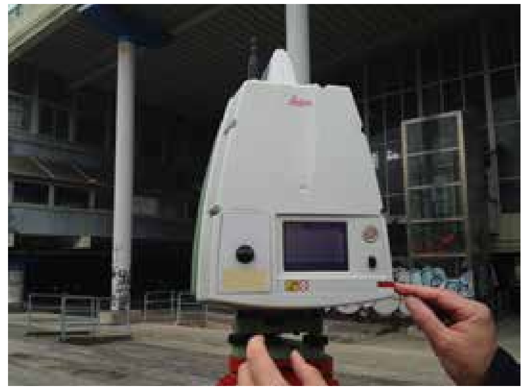

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FIG. 3 Some pictures of the field activities performed on site

The deviation analysis, performed by Hochtief as a consortium partner, has been performed using the 3DReshaper software and it represents the core activity of use case 1. The deviation analysis process for detecting modelling errors involved several steps.

First, the as-is BIM data and the point data have been be aligned, since they had different locations. Ideally, the entire BIM could be compared with the point data in a single operation, but existing software is not capable of handling the large data sets that would be involved and also cannot easily visualize deviations in building interiors. To address these limitations, we segmented a facility into smaller surfaces, such walls, floors, and ceilings of individual rooms, and then conduct deviation analysis separately on each surface. The data for each surface was first segmented from the as-is BIM and the point cloud data.

Then, deviations have been computed between the segmented BIM data and the point cloud data. Next, the deviations have been visualized in the form of a deviation map.

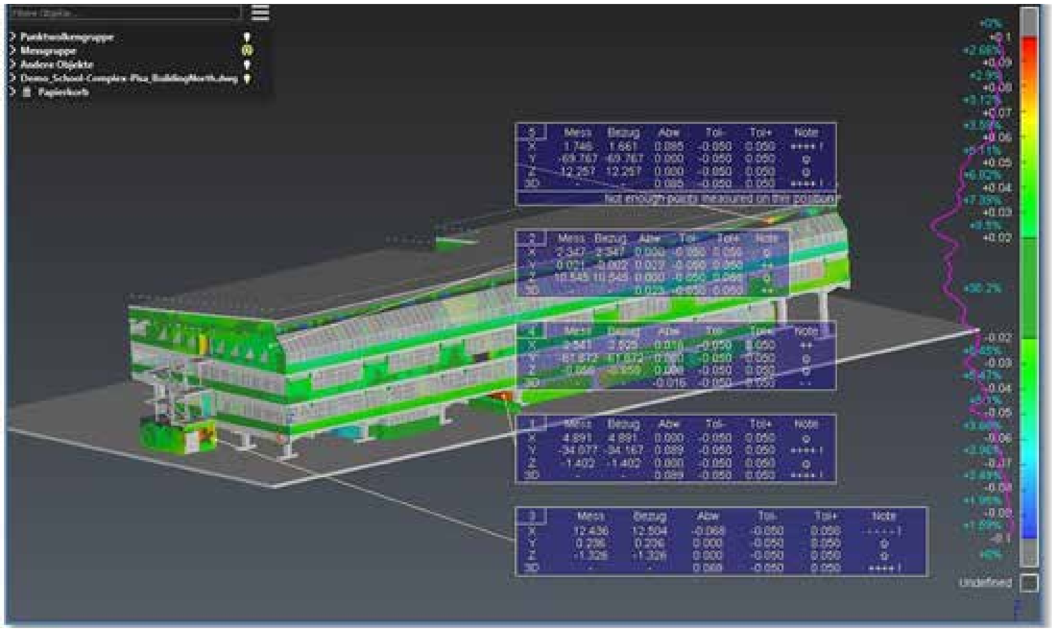

FIG. 4 Deviation information of specific points.

The deviation maps have been then analysed to determine the cause of each significant deviation. Finally, the results have been summarized and combined with the analyses of other surfaces. The following main functionalities for the INSITER applications have been demonstrated:

- Process of effective BIM modelling (modelling on base of 2D drawings, evaluating the (geometry of the) BIM models on base of laser scans, optimize the BIM models to match the as-is situation;
- Re-use laserscans of another laserscanner to create TruViews to support site teams with exact geometrical information (by avoiding that the site team has to use expert software).

3.2 USE CASE 2: BUILDING ENVELOPE – CHECKING OF THERMAL PERFORMANCE ON 2D COMPONENTS

The second use case for the existing School Complex involved the assessment of 2D façade panels, to verify the thermal performance of the envelope and identify the presence of thermal bridges, that have been detected using infrared camera. This activity was aimed at verifying the energy performance of the building envelope elements, as per Owner's request. Therefore, the use case was a development of Step 1 – Mapping of the INSITER methodology and can support in the self-inspection phases, such as diagnostic and building assessment, pre-construction, post-construction, and maintenance.

A first analysis has been carried out by standard inspection techniques. This analysis has provided only "qualitative" information about the thermal bridge asset. In order to evaluate the thermal bridge impact on the building performance, the following steps have been followed:

- Analyzing plans, sections, details, shop-drawings, as-builts and technical documentation (if available) in which the geometric and technological characteristics of the building are reported;
- Visual inspection in situ in order to detect visible areas of mold on the building envelope;

- Use of the infrared camera to detect the most discrete discontinuities at sight. The thermal image is visible, even to unskilled personnel, as well as the heat flow and thermal dispersions associated as pillars in wall, beams, etc.

The inspections and surveys have been performed by a FLIR B60 camera, capable of capturing the energy emitted by hot bodies (-20°C <T <120 ° C) in the form of electromagnetic radiation of the band "infrared" / LW (long wave) and turn it into thermographic image. The analysis has been conducted in the passive voice, i.e. using the direct solar radiation incident on surfaces and natural convective flows.

1

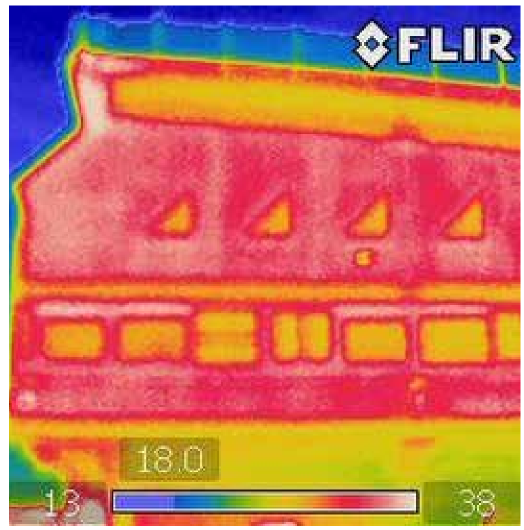

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FIG. 5 Example of real and thermal image on the case-study in Pisa

The investigation has been carried out on different portions of the main building, depending on the floors (first, second and third floors) and the exposure (mainly East, North and West). The survey has detected the temperature of different materials and building components. for each thermal image acquired, the outside air temperature and the indoor air temperature have been measured. Windows and openings were closed. The scales on the thermal image have been set automatically (autoscale). The framing has been carried out in a more frontal way and that the area framed by the camera is also taken with a camera in the visible area. The two images have been taken to result as aligned as possible. The pictures below show external and internal view of the facility during the inspection.

The thermographic investigation of the building envelope evidenced that the methodology based on IR camera is very powerful since it is able to visualize any area of the wall exhibiting a different emission. In fact, parts of the envelope made of different materials or having different colours are recognizable due to their different emissivity. The thermal transmittance can be calculated from the stratigraphy following the UNI EN ISO 6946:2008

The calculated thermal transmittance of the panel is 3.817 W/m^{2}K. In addition, only as a verification method, a partially destructive investigation has been performed in the external wall, by a drilling to identify its stratigraphy.

On the basis of the collected data, AICE has also carried out a similar thermal simulation with design new condition: the analysis has been carried out by installing an external insulation for the opaque panels, consisting of 15 cm thick expanded polystyrene panels. This thickness allows compliance with the transmittance values for the building envelope as per applicable standards. A comparison was also made between current energy consumption and those after the intervention, and the payback period was calculated. An additional design scenario has been developed, considering the replacement of the windows. The cost estimate only focused on the envelope and does not consider the additional cost to "adapt" or replace the existing HVAC system. The simulation scenarios showed that the effort for refurbish the building envelope and to upgrade to current energy standards is very significant. The inspections and simulations carried out using the INSITER methodologies were of fundamental importance for defining the refurbishment scenarios. These results constituted the decision-making basis for the building owner to plan the interventions on the building.

3.3 LESSONS LEARNED FROM CASE STUDY ON-SITE APPLICATIONS

The main goal of the case study in Pisa was to capture as-is situation of the building envelope and provide refurbishment scenarios to be compared, considering that no information on the building was available except from some 2D drawings. The first phase of mapping has been developed using INSITER methodologies to improve and enhance standard practices; the second part, i.e. the development of possible scenarios: the INSITER procedures during on site measurements and off site simulations have speed up the elaboration of different design options.

Thus, A.I.C.E. Consulting (as SME of building inspectors and engineers, partner of INSITER) has been able to capture the requirements and provide effective design solutions to the Building Owner, based on actual condition of the building envelope.

From the geometric analysis and the calculation of deviation analysis (Use case 1) of this case study, it has been learned that is not efficient to model on base of point clouds, since this would need too much computing power, because those point clouds are very large and hard to handle. The exactness of the point clouds cannot be transferred into a 3D model and therefore abstractions would be needed (cracks and really minor changes of surfaces are included in the point clouds, but should not be included in a BIM model). In addition, lots of items which are shown in laserscan are not relevant for the BIM model itself – this abstraction makes modelling very hard and time-consuming. There are approaches to automate the BIM object creation (e.g. for pipes and ducts), but the effort to validate if those items have been correctly been transferred from points to BIM objects, is far greater than modelling the objects on base of 2D drawings. Finally, it has been found that deviation analysis is a great tool to validate the correctness of available 3D data.

From the thermal inspections and the calculation of the transmittances (Use case 2) of this demonstration case, it has been learned that, according to the test conditions (mainly environmental ones) and the type of the building (new construction or renovation), it is possible to adopt the most appropriate technique and test procedure that allows having the best compromise between expectations, available resources and time. In this demo case, an analysis of the test conditions (season, possibility of conditioning, etc.) and the condition of the building under renovation made it possible to establish that the fastest, least expensive and less invasive method was the drilling coupled with analytical calculation.

4 CONCLUSIONS

Bridging the gap between predicted and measured performance is crucial if the design and engineering stage is to provide serious input to the delivery of buildings that meet their (quantified) ambitions, such as High-Performance Buildings, Zero Carbon and Net Zero Energy Buildings (de Wilde, 2014). The Zero Carbon Hub report suggests that the industry needs to move to a situation where over 95% of houses meet the performance required (Zero Carbon Hub, 2010). This gap between "as-is" and "to-be" would be reduced or eliminated by introducing novel technologies on building site, such as practical use of BIM and Augmented Reality techniques. Within the scope of the INSITER project, a comprehensive methodology has been developed and tested on site for real cases studies, in order reduce the amount of errors. The research has developed, in different type of projects (new construction and refurbishment, including commissioning and maintenance), by developing guidelines of BIM-based self-inspection and for self-instruction. In addition, protocols of the selected hardware instruments have been outlined and testes in the lab and on site, in order to improve the use and output quality of tools such as 3D scanner, thermal cameras, sound brush etc: such procedures have been tested on site and included in the INSITER App (beta version), to be used by construction stakeholders.

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Materiality and Embodied Carbon Considerations in Contemporary Curtainwall Systems

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Abstract

It's not all about digits! The focus on digital processes as technological enhancements obfuscates fundamental problems in existing curtainwall technology and practices. Digital processes are certainly important, with great potential to amplify the efficacy of well-conceived façade systems and complimentary design and deliver practices. But digital processes cannot remedy fundamental problems in basic technology and practice; a fuel-injected jalopy is still a jalopy, just a faster jalopy. What is needed is a fundamentally transformed façade technology possessed of orders-of-magnitude enhancement in durability performance. Embracing this constraint requires an inside-out rethinking of the building skin.

Little has changed in curtainwall technology since its inception in the mid-twentieth century. One can speculate that that the industry is ripe for disruptive change. Scott Thomsen, former president of the Global Glass Group for Guardian Industries, claims that, "The glass industry is mired in incrementalism. Industries die if they don't make large changes. Industries fail without a major step change every 30 years." The same can be argued of aluminum and glass curtainwall technology. Incrementalism in curtainwall system development has yielded a progression of thermal break techniques in aluminum framing systems, double-skin designs, closed-cavity and pressurized cavity systems, increasingly elaborate shading strategies, all characterized by growing complexity, materiality and cost. Yet vital considerations of durability: maintainability, repairability, upgradability and adaptability—the (dis)-abilities—have been largely ignored, compromising façade system durability. A direct result of this is the growing number of early mid-century curtainwall buildings in need of façade retrofit, and where a lack of viable options typically necessitates complete system replacement, this at great cost to the building owner and disruption to the building occupants. The problem is exacerbated by the premature service life termination of the highly durable glass and aluminum material components of the system, both high embodied carbon materials, contributing to an enlarged lifecycle carbon footprint for the building. The root problem here is the failure of these early curtainwall systems to properly account for an appropriate service life in their design. This paper presents recent research that reveals this problem to be equally true of today's curtainwall system designs, creating the very real probability that we are busy building tomorrow's problems today. The research also provides relevance and insight to the problem of embodied carbon in existing curtainwall technology, with root cause resulting from the failure of curtainwall system designs to anticipate the inevitable effects of the (dis)-abilities and their impact on system durability. The examination of these problems suggests a trajectory to future technology centered on resolving the (dis)-abilities that resolves these issues, resulting in façade systems with the potential of indefinitely extended service life.

Keywords

curtain wall, façade, embodied carbon, embodied energy, durability, adaptability, maintainability, upgradability, service life

1 INTRODUCTION

Incremental developments in architectural glass—e.g., a 4th coating of silver to improve low-e performance; and framing systems—deeper thermal breaks improving thermal performance but compromising structural capacity; are yielding diminishing returns. The continuing design focus on reducing energy consumption during a building's operational phase is resulting in increasingly complex and material intensive solutions with little or no consideration given to the embodied carbon impact. This produces a "front-loaded" carbon footprint that may require many years of energy savings to reconcile. Recognition of the time-value of carbon brings such practice into question. The need for carbon savings from buildings and the built environment to mitigate the impacts of climate change is critical and immediate. The value of carbon reductions in keeping average global temperature increase below 2°C decreases as time progresses.

Improving operational carbon efficiencies while ignoring the embodied carbon impact of design decisions is no longer acceptable practice. Performance efficiencies of a unit assembly may be offset by material inefficiencies. Simply put, increasing complexity and materiality are at cross-purposes with carbon emission reductions, yet are seldom considered in contemporary glass and metal curtainwall design.

It is time for a radical rethinking of the building skin.

2 METHODOLOGY

This paper is based on dissertation research involving curtainwall design, delivery and renovation practices investigated through a mixed-method approach combining a literature review—extending through multiple disciplines and topics—with surveys, workshops, and case studies, and combining quantitative analysis with qualitative analysis built largely on three decades of experience with curtainwall technology (Patterson 2017, 18-40). This methodology is appropriate to the research intent of a broad-based reassessment of the development and current state of curtainwall technology that could lead to reconceptualization, as opposed to a purely quantitative and incremental inquiry into a focused attribute of the technology. The literature review through diverse disciplines was particularly productive and included: building science, social science, facilities management, industrial ecology, engineering and construction, historic preservation; and topics ranging through sustainability, resilience, service life prediction, obsolescence, consumer products, durability planning, lifecycle assessment, construction and demolition waste, renovation and retrofit, building materials, and maintenance.

3 THE PROBLEM WITH CARBON

Anthropogenic climate change, fueled by massive loading of carbonbased emissions into earth's oceans and atmosphere, is widely recognized as an existential threat to humanity (Guterres 2018). The building sector is a leading contributor to this problem, producing over 40 percent of carbon emissions in developed nations like the United States (Architecture 2030). Reducing the carbon footprint of buildings is urgent and imperative.

3.1 WHOLE LIFE CARBON

The appropriate metric for evaluating carbon emissions from a building is whole-building lifecycle carbon or whole life carbon (WLC) (Sturgis 2017). As the term implies, this includes carbon produced over the entire building lifecycle from construction through end-of-life processes. WLC is the sum of carbon produced from building operations, or operational carbon, and that resulting from building construction, maintenance and disposal, as well as from the production of materials used in the building, referred to as embodied carbon. The measure of carbon produced from building operations has been the primary focus of building performance evaluation, but this ignores an important component of WLC.

3.2 EMBODIED CARBON

Embodied WLC accounts for the materiality of a building and the carbon emissions associated with the production, installation and maintenance of those materials over the full building lifecycle. This includes emissions starting from raw material extraction through cycles of transport, processing, fabrication and assembly, and those produced during the construction process. Long regarded as less than 10-20 percent of WLC (Ramesh, Prakash & Shukla 2010, 1592-600), material impacts were largely ignored, but recent research is revealing a different reality. Embodied carbon from buildings situated in a mild climate can represent 35 percent of WLC (Karimpour, Belusko, Xing & Bruno 2014). Studies have shown that embodied impacts could constitute as much as 65 percent of WLC for a typical office building (Cole & Keran 1996, 315), and 50-60 percent in residential buildings (Rauf & Crawford 2015, 147). Enhanced operational efficiencies effectively increase the relative % of embodied carbon in WLC. Low energy buildings evidence a higher embodied carbon profile than conventional buildings (Sartori & Hestnes 2006, 256-7), as material impacts are swapped for operational carbon efficiencies.

A building commences its operational phase having already amassed a significant carbon debt. Maintenance and renovation activities during the operational phase add to the embodied carbon footprint, as does the final disposition of the building: recycling, repurposing and reuse, or disposal. Importantly, the majority of embodied carbon—60 to 80 percent—derives from materials (Simonen, Rodriquez, McDade & Strain 2017).

3.3 TIME VALUE OF CARBON

Emission reductions need to happen as soon as possible over the next 10 to 25 years to achieve peak emissions that keep increased average global temperature below 2°C (IPCC 2013) (Fig. 1). Embodied carbon emissions are largely front-loaded, occurring at the very beginning of a building's lifecycle (Strain 2017). Carbon savings in the short term are of greater impact than savings over an extended time period, as may result from operating efficiencies over a full building lifecycle. Evaluating carbon saving strategies from improved operating efficiencies must be carefully weighed against the carbon cost of the materials employed to achieve those efficiencies.

High-performance façade assemblies with enhanced energy efficiency are often achieved through the layering of additional materials, e.g., double-skin systems, with no consideration given to the embodied carbon emissions associated with those materials. The time value of carbon calls such practices into question. An analysis by Jones (2014) showed that the payback period in carbon savings for the added embodied carbon of a triple-glazed verses double-glazed insulated glass unit (IGU) was about 20 years, approximately the service life of the average IGU. Frey (Frey, Dunn

& Cochran 2011, 84) found that retrofits reducing energy consumption by 30 percent could take as much as 80 years for energy savings to offset embodied carbon expenditures resulting from the retrofit. Operational carbon reduction strategies must be evaluated in terms of embodied carbon cost and yield a positive payback as early as possible, and certainly within the service life of the product or assembly.

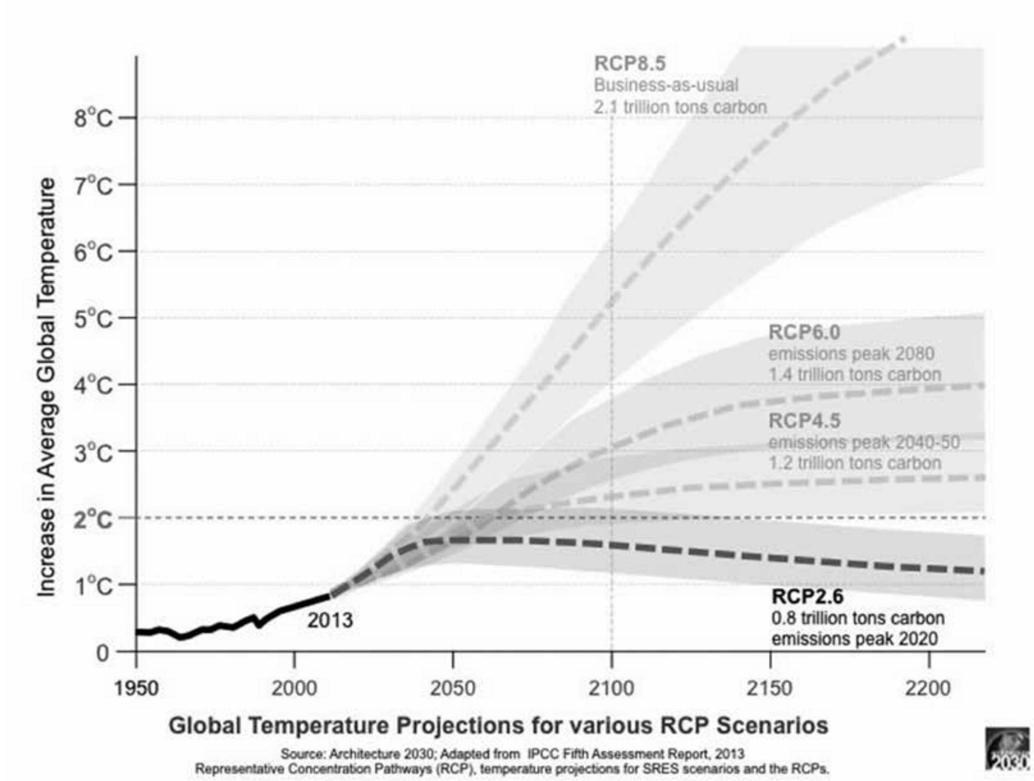

FIG. 1 Global temperature projection scenarios. The goal is to keep average global temperature increase below 2°C. *(Architecture 2030)*

4 EXTENDED SERVICE LIFE AS AN ANTIDOTE TO EMBODIED CARBON

The issue of embodied carbon brings new considerations to the forefront. Extending the service life of a product or assembly is a straightforward way to reduce lifecycle embedded carbon. Doubling the service life of a building or system roughly halves the environmental impact resulting from its construction (Yost n.d.).

4.1 DURABILITY, CHANGE AND OBSOLESCENCE

Buildings change over their lifecycle. The physical aging and deterioration of finishes, materials and systems—the forces of degradation—bring changes that are most commonly associated with the attribute of durability. But the dominant change agent is the changing needs and expectations of the building users (Brand 1994, 2). This type of change can render a building obsolete long before the forces of degradation. Obsolescence in buildings is the state at which they become unsuitable for their intended purpose. It can take many forms. Tab. 1 lists the dominant forces of obsolescence.

Reasons for obsolescence include factors having nothing to do with a building's design, such as urban redevelopment, poor construction or maintenance quality (Athena Institute 2006, i). Yet many point to the critical role of design in anticipating and accommodating the forces of obsolescence.

PHYSICAL DETERIORATION
economic obsolescence
functional obsolescence
technological obsolescence
changes in social context
obsolescence due to building envelope
legal obsolescence
aesthetic obsolescence
environmental obsolescence

TABLE 1 Categories of threat to service life *(from Silva, de Brito & Gasper 2016, 16)*

Design largely determines the ease of future change of a building or building system, along with the social, economic and environmental impacts of these changes (Khasreen, Monkiz, Banfill & Menzies 2009, 677). Sarja (2005) and Slaughter (2001) tie obsolescence to building and system designs that are incapable of adapting to changing functional, economic and cultural conditions. Obsolescence, and thus durability, is directly linked to adaptability (Kesik 2002, 307, 312, 402). Some few architects understand this, Sir Richard Rogers among them:

"I believe that many architects misjudge the private needs of buildings. The rate of change in society - and you can pick the computer or whatever you want as a symbol - makes long term prediction impossible and inflexible building unreasonable [...] What we can do - and this is the key to much of my work - is to design buildings that allow for change, so they can extend their useful lives [...]"

Sir Richard Rogers (Caplan 1988).

5 ADAPTIVE CAPACITY

Adaptive capacity is a term borrowed from ecological science (Smit & Wandel 2006), reinterpreted here to mean the capacity of a building or its major systems, e.g., façade system, to accommodate adaptation to changing conditions of use and service environment so as to resist the various forces of obsolescence in a manner to optimize service life and lifecycle carbon footprint.

The drivers of obsolescence appear to be accelerating the process. Adaptability is a prime strategy to prevent premature obsolescence and enhance the sustainability of the built environment (Arge 2005, 127; Kincaid 2000, 155). Roger's Lloyd's Building (1986, London) anticipates the need for future adaptability by separating building services from useable space, making services easily accessible and upgradable with minimal disruption to ongoing building operations (Iselin and Lemer 1993, 35-6). Hartkopf and Loftness (1999, 385) recommend modular, expandable and reconfigurable design strategies to accommodate the adaptability necessary to avoid obsolescence. The service life of a building is often determined by its ability to accommodate change. Building designs must anticipate future renovation with systems and components that are easily maintained, replaced and upgraded (Strain 2017, 6).

Novel systems and unfamiliar service environments challenge system service life (Nireki 1995, 404). Climate change and escalating complexity in façade systems are current dominant trends. Climate change renders the practice of determining design loads based on historical data obsolete, yet this practice continues. Even predicted data can only yield an approximation of what the rapidly evolving future conditions may bring. The ability of buildings and their systems to adapt to these changing and unforeseen conditions may well be critical. "Unanticipated changes may be the leading cause of obsolescence in buildings. The uncertainties of climate change exacerbate this problem" (Patterson 2017, 139). The pursuit of enhanced performance combined with increased geometric and material variations has significantly amplified the complexity of curtainwall systems. The attributes of adaptability mentioned above: regularity, modularity, expandability and reconfigurability are often compromised by customization and complexity. High-performance façade systems and irregular façade geometries achieved at the expense of complexity and materiality may be compromising the sustainability and resilience of buildings and urban habitat.

Cost and convenience considerations are also tied to adaptability, along with related considerations of maintainability, repairability and upgradability. Cost and disruption to ongoing building operations can represent formidable barriers to maintenance, repair and renovation. Adaptive reuse strategies can approach and even exceed replacement cost, calling the original design into question (Kesik 2002, 313). This can be the case with curtainwall systems, which characteristically fail to anticipate the need for future retrofit (Patterson, Martinez, Vaglio & Noble 2012). Relatively small premiums in original construction cost can enhance the adaptive capacity of a curtainwall system, yielding significant dividends over a building's lifecycle. Oversizing façade anchorages and the utilization of cassette strategies to facilitate the change-out of façade glass are useful examples. This conflicts, however, with the dominant consideration of minimizing first cost, which short-circuits the consideration of strategies that could extend service life and reduce both lifecycle cost and carbon footprint.

As a major building system, the adaptive capacity of the façade system was found to be a critical yet neglected consideration. "That curtainwall systems are not designed to accommodate future retrofit represents a threat to the service life and quality of both the façade system and the building" (Patterson 2017, 137). But it is not just retrofit that must be accommodated as a function of adaptability, it is also considerations of reuse, maintenance, repairs and recycling that must be anticipated in system design. It is vital to the realization of sustainability and resilience goals in the built environment that metrics and strategies be developed in support of enhancing the adaptive capacity of contemporary curtainwall systems.

6 MEET THE (DIS-) ABILITIES

A critical set of considerations was identified - characterized as disabilities - became a focus of this research. The (dis-) abilities - durability, adaptability, maintainability, repairability, upgradability, reusability and recyclability - are recognized as primary attributes of façade system performance that are routinely ignored in system design, thereby disabling rather than enabling these systems in optimizing their potential service life and WLC footprint.

Durability

Durability as used here is the temporal measure of a material, component or system to resist the various forces of obsolescence and perform its required function in a given service environment.

Premature obsolescence results in shortened service life, wasted durability potential and amplified embodied carbon.

Adaptability

Adaptability promotes durability. Adaptability is the ability of a material, component or system to accommodate changing conditions of use and service environment in a manner to avoid premature obsolescence. The following abilities: maintainability, repairability, and upgradability amplify the adaptive capacity of a material, component or system.

Maintainability

Maintenance planning and practices are vital to achieving optimal service life with virtually all materials, components and systems (Donca et al. 2007). Buildings and façade systems should be designed for ease of access and maintenance.

Repairability

Repairability is an important performance requirement for buildings and building systems (Straube & Burnett 2005, 40). Similar to the requirements for maintenance, repairability necessitates consideration of restoration, but also the ease of component removal and replacement, including those components requiring minimal to no maintenance.

Upgradability

Upgradability must be an established priority in adaptive product-service system designs (Pialot and Millet 2014, 379-84). Upgradability is a particularly relevant concept with respect to the façade system. A façade system design that fails to accommodate efficient upgrades through a building's lifecycle may limit the service life of the façade system and potentially even limit the survivability of the building itself. Consideration should be given to the potential for system reconfiguration as an attribute of upgradability.

Reusability and Recyclability

Service life planning must address attributes of reuse and recycling for all materials, components and systems (Meadows 2012).

7 MATERIAL MATTERS

Consideration of embodied carbon elevates the importance of material selection in building and façade system design. Materials vary considerably in their embodied carbon profile, or the amount of carbon produced through their manufacturing lifecycle. The metric used here is embodied energy use intensity (EEUI), which is derived from a unit of material times an embodied energy coefficient developed to account for locational variations including regional fuel sources, transportation practices and other factors. Various databases have been developed with embodied energy coefficients for a wide variety of materials, such as the ICE database (Hammond & Jones 2011). Tab. 2 utilizes these coefficients to establish embodied energy use intensity for the typical components comprising an aluminum and glass curtainwall system, pairing those values with the average service life for each. As the coefficients indicate, glass, and particularly aluminum, are high intensity materials. Ignoring the units, it is easily seen that the glass and aluminum dominate the assembly EEUI, comprising 93 percent of the total assembly per unit area.

Materials age differently. Differential durability is the consideration of this difference in the design and evaluation of an assembly. The durability of a building, façade system or component is ultimately determined by its weakest link, or the component with the shortest service life (Kesik 2002, 306). Thus, the indefinite service life of raw float glass (good for 100s of years in the building façade) is reduced to a 20-30-year timeframe when assembled into an IGU by the relatively short service life of the IGU seals. With no way to easily repair the bonded IGU, a failed unit requires replacement. Differential durability has a knock-on effect. No good way to replace the IGU in a curtainwall system may necessitate the replacement of the entire system. Such was the circumstance with the 2014 renovation of the façade system for the Javits Convention Center where analysis revealed that system replacement was cheaper than partial renovation (Golda 2014). Survey research involving over 600 building façade retrofits revealed complete façade replacement as the leading façade renovation practice over partial renovation strategies (Martinez, Patterson, Carlson & Noble & 2015). This is the result of the lack of viable renovation alternatives embedded in the original system designs.

CW UNIT MAKEUP	EMBODIED ENERGY COEFFICIENT (kBtu/lb)	WEIGHT (lb/sqft)	EMBODIED ENERGY USE INTENSITY (kBtu/sqft)	%	AVERAGE SERVICE LIFE (years)
Insulating Glass Units	10.73	6.75	72.43	26	20-25 [1]
Aluminum Framing	66.21	2.24	148.45	53	60-200 [2]
Lift Lug and Anchor	66.21	0.16	10.38	4	60-200
Fasteners	24.38	0.12	2.83	1	
Shadowbox - Alum Panel	66.21	0.44	29.31	10	60-200
Insulation	9.18	0.67	6.12	2	
Backpan - Galv Steel	12.25	0.37	4.50	2	
Gaskets & Seals	26.51	0.23	6.10	2	10-20 (Meadows 2014, 55)
Totals		10.97	280.11	100	

1 The raw float glass, the dominant component, has an indefinite service life (centuries).
2 Aluminum finish is the weak link: anodizing 30+ years; polyester powder 15-25 years; PVDF or PVF2 20+ years (Mayer 2006).

TABLE 2 Embodied energy approximation of baseline CW system using ICE LCI data *(Hammond and Jones 2011)*, with predicted service life averages *(Patterson 2017, 172)*

Furthermore, the prospect of curtainwall system replacement on a tall building in a dense urban environment like New York City, with the accompanying expense and disruption to ongoing building operations, can raise the consideration of building replacement as a viable alternative (Browning, Hartley, Knop & Wayne 2013). The embodied impacts of this progression from partial façade renovation to complete building replacement are evident. The remedy here is a practice of harmonizing the service life of the components that comprise an assembly and providing for the easy repair and replacement of the less durable components such that the full potential service life of most durable component of the assembly can be realized. Cooper (2010, 8), in discussing consumer products, states, "Deliberate effort needs to be made to utilize fully a product's potential life-span, through careful use, regular maintenance, repair, reconditioning (e.g. upgrading) and reuse of functional items (rather than disposal)." The same is true of the millions of buildings that comprise the global building stock. The building stock of any nation represents a significant fiscal and cultural asset requiring preservation for future generations (Nireki 1996, 405). It is imperative that appropriate service life goals for buildings and their façade systems be established, along with effective strategies to realize those goals, including building and system designs that anticipate and accommodate future maintenance, renovation and adaptability requirements (Patterson 2017, 174).

8 HOW LONG SHOULD A BUILDING (OR IT'S FAÇADE SYSTEM) LAST?

Inquiry produced no consensus on how long a building or a building façade system should last. The literature revealed opinion ranging from 15-30 years to 1000 years to "indefinitely" with respect to buildings, and from 20-50 years for curtainwall systems (Patterson 2017, 150). Despite the massive commitment of resources represented by large commercial and residential building projects, there is no explicit requirement for establishing a building service life. Even LEED Platinum buildings have been routinely developed with no definition of building service life. Durability and maintenance planning are challenging in this context.

The concept of resilience in ecological systems recognizes redundancy as an attribute, and the potentially compromising effect of over-efficiency (Fisher 2013, loc. 306-393). The pursuit of economic and thermal efficiencies in contemporary curtainwall technology has led to systems with amplified complexity and compromised adaptive capacity. Contemporary curtainwall systems are less adaptable than their earliest progenitors, the stick systems first used at the advent of curtainwall technology in the mid twentieth century. Today's factory assembled unitized systems are typically bonded modular assemblies interlocked with each other as they are sequentially fixed to the building structure. No consideration is given in their design to future requirements for maintenance, repair or retrofitted upgrades. This is as true today as it was of those early stick systems that are now proving so problematic to retrofit. This creates the very real prospect that the building industry is extremely busy building tomorrow's problems today.

Solutions may be found in the concept of renewable systems (Patterson 2017, 175), systems designed to facilitate cycles of maintenance and partial renovation to extend service life indefinitely. A façade system at the end of its lifespan may not contain a single original component yet have seen continuous service in the building skin. The embrace of such constraints fundamentally changes the design parameters of the system. Consider the stack joint of a contemporary curtainwall system (Fig. 2). Variations include single leg (as pictured) and double leg designs, but all involve a characteristic interlocking as illustrated in the figure. The "business" end of the system, at least in terms of the air and moisture seal, is the air and moisture seals incorporated at the very tip of the leg. These seals are in compression and are allowed to slide up and down in their enclosing channel to accommodate even the extreme movements that can occur in tall buildings. This is one of the great strengths of these advanced unitized system designs.

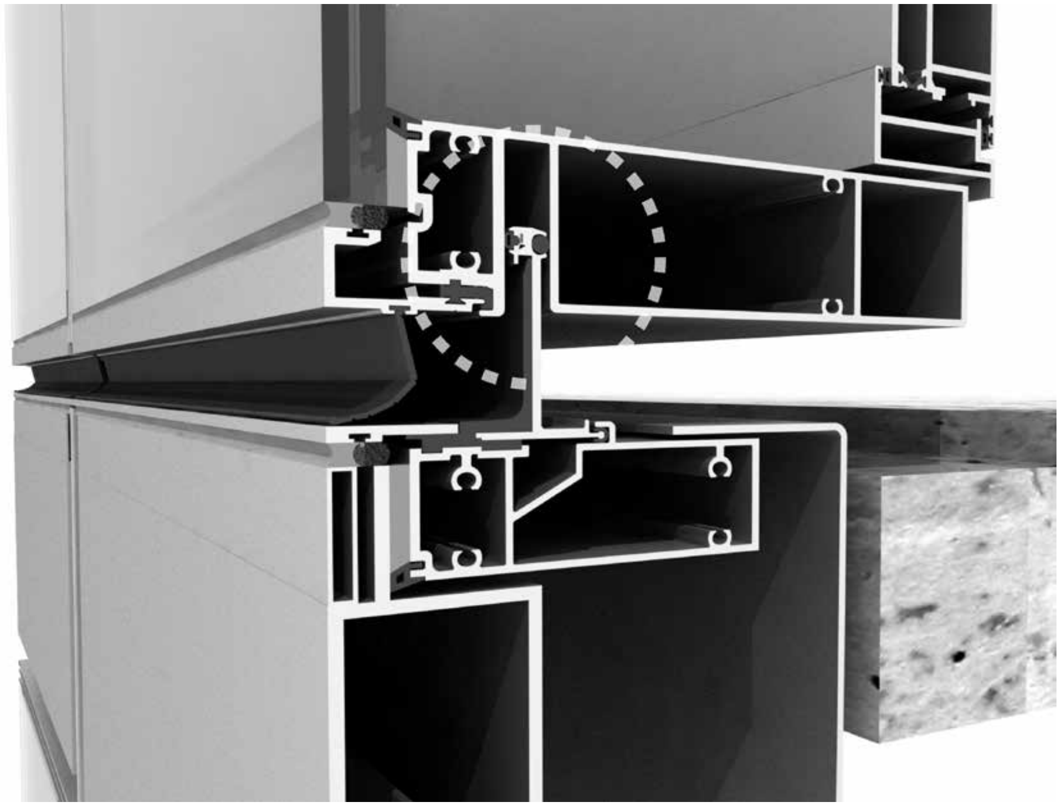

FIG. 2 Typical stack joint of unitized curtainwall system with concealed air/water seal (in dotted circle), which is inaccessible for inspection, repair, maintenance or replacement after initial installation *(Source: Advanced Technology Studio – Enclos)*

The problem is that once this unit is installed, this seal, critical to performance throughout the system service life, is buried in the assembly and inaccessible for inspection or servicing for the lifespan of the system. The façade industry represents these curtainwall products as zero-maintenance systems when, in fact, they prove to be unmaintainable systems. Another obvious vulnerability is the failure to accommodate an easy replacement of the IGU, typically the weak link in the façade system, with new and better performing product.

There is also the consideration of reuse and recyclability. Reuse practices are far superior to recycling in most cases. Façade systems, like the buildings they clad, are not designed with repurposing and reuse in mind; many are unique one-off configurations providing no potential for reuse. While much of the aluminum in curtainwall systems is recycled the architectural glass is not. The secondary processing of the float glass involving laminating, coating and bonding into assemblies renders them economically unrecyclable. Some of this glass may be ground and used as fill material in asphalt or similar products, but much of it ends its lifespan in landfills. Float glass is a material with remarkable properties of durability and recyclability: good in the building skin indefinitely until broken and infinitely recyclable to virgin material quality with less energy than the making of new material. The IGU provides an excellent example of a product failing to embrace appropriate design constraints to address the (dis)-abilities. The result is a product that collapses the durability of float glass from 100s of years to a 20-30-year timeframe and renders the material unrecyclable in the process. That the building industry refers to these as high-performance glazing products reflects the dominant disregard for important considerations of materiality and durability, considerations necessary in optimizing WLC and the pursuit of carbon neutrality in the built environment.

9 SUMMARY & CONCLUSIONS

The materiality and embodied carbon of contemporary curtainwall systems is investigated and found to be a significant problem, further exacerbated by the time value of carbon. The building carbon equation used in practice is incomplete; operational energy efficiencies are being realized by shifting energy consumption from the operational to the embodied side without including embodied carbon in the equation, thereby obfuscating the Whole Lifecycle Carbon footprint.

Extended service life is identified as an effective countermeasure in offsetting the lifecycle carbon impacts of this materiality. Extending service life brings important design considerations to the forefront, considerations typically neglected in current practice. Durability, change and obsolescence are explored in the context of the building skin, leading to the relevance of adaptive capacity as a resilience and sustainability consideration in building façade design. A set of design considerations for the development of future façade systems is identified that includes: durability, adaptability, maintainability, repairability, upgradability, reusability and recyclability.

The material profile of a generic glass and aluminum curtainwall system is analyzed, and glass and aluminum, both high embodied carbon materials but with long potential service life, are found to comprise 93% of the material composition by unit weight. The long potential service life of these high embodied energy materials is, however, significantly compromised by the sealants, seals and finishes that comprise the minority material content of the assembly.

In the absence of appropriate service life goal definition, curtainwall system designs are found to fail to anticipate the need for future maintenance, repair and retrofit that could avoid obsolescence and extend system service life. Moreover, the trajectory of curtainwall development is found to be toward increased materiality and complexity and decreased redundancy—all in the pursuit of greater operational energy efficiency—further compromising system adaptability and resistance to the forces of obsolescence. Potential solutions are suggested in a concept of renewable systems designed to accommodate perpetual cycles of maintenance, repair and partial renovation to extend service life indefinitely.

The early curtainwall systems constructed in the mid 20th century are already a problem of today. Those being constructed now and in the foreseeable future are the problem of a tomorrow that will arrive all too rapidly. Major building projects should be "designed for the ages" using renewable strategies that accommodate the indefinite extension of building and façade system service life as serves future needs.

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A Visual Digital Tool to Assist the Concept Design of Façades

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Abstract
During the early design stages, when the massing of a building is defined, design teams make the decisions that have the biggest impact during the life of a project, as they set the key parameters which will affect all the different aspects of the design. The tools informing the designers in this phase of the project need to be very agile and adaptable, in order to respond to the specific needs of the development under consideration. In the last few years a number of digital tools have tried to narrow the gap between the need for quick answers and the requirement of comparing a large number of options via parametric assessments. One design criterion that is not generally addressed in an engineered way is the availability of significant views from the inside of the building, even if this has a substantial impact on the final commercial value of the project. The lack of viable ways of answering questions that are not traditionally codified in engineering terms has very detrimental effects. If design teams are not able to combine in an easy way different levels of information, they are often forced to put aside some key design criteria and hope that satisfying solutions will be found during the later stages of the design development. It is very likely that in this way huge opportunities to increase the value and the quality of a project are missed. This paper shows how a visual digital tool was created for a specific project to provide guidance during the selection of the massing of a large development, combination of both residential and commercial areas. The aim of the tool was to compare different massing options in terms of availability of viable views from the apartments of the residential building and of more traditional, quantifiable criteria, such as the availability of daylight and direct solar irradiance on the public spaces surrounding the development. The tool presented herein can provide quick comparisons in terms of the different design criteria and incorporates a combination of quantitative and qualitative contents that ease the communication between the different parties of the design team. Such an approach has proven successful as it eliminates some of the barriers towards a holistic design.

Keywords
massing, visual tool, views, daylighting

1 INTRODUCTION

Building envelopes have to deliver high levels of performance in order to minimize the energy use to control the internal environment and provide good comfort for the occupants. At the same time, they define the aesthetics of buildings and cities, hence their appearance is key for the definition of the architectural success of projects and their financial returns for the developers.

There are a large amount of tools that help design teams address the 'performance' questions. Arup Solar is an app developed in the last few years to provide immediate answers to design teams with respect to how the building envelope needs to perform to control solar gains and to the potential for on-site power generation. The innovative style of the tool has removed many of the barriers that made performance-driven design extremely hard.

This paper shows how a new digital tool can also help answer questions that traditionally do not belong to engineers as it is hard to associate measurable parameters to quantify the design criteria. The specific topic presented in this paper is the design for the views, i.e. how a digital tool can compare massing options with respect of how different building shapes can maximise or reduce the views from the inside to the outside.

By considering both performance levels and views at the same time, engineers can provide a better support to clients and architects.

2 METHODOLOGY

The most critical decisions for a project are made during the early design stages, but there is a lack of tools that provide adequate support to inform the concept of buildings(Granadeiro, Duarte, Correia & Leal, 2017). For these tools to be effective, it is fundamental to identify the right balance between accuracy and agility in the calculation process and to provide an easy way of interpreting the results. Such process is a continuous development that tries to meet the needs of the authors' clients. This paper presents the current step of development of a visual digital tool which informs the early stages design of building envelopes and massing by combining three levels of information:

- Solar performance requirements of the envelope and potential of on-site energy generation: this is the output of the Arup Solar assessment (Donato, Zemella, Rapone, Hussein & Black, 2017);
- Quantitative assessment of the views towards specified points of interests from the different parts of the façade – there is extensive research demonstrating the importance for occupants to have unobstructed views towards green spaces, for example (Chen-Yen & Ping-Kun, 2005);
- Qualitative assessment of the views from the different parts of the façade.

There have been previous attempts to include a quantifiable criterion of available views as part of an optimization process for the design of façades (Rapone, Saro & Zemella, 2013). This new approach tries to simplify the way the information is processed and made available. The use of optimization algorithms to drive the concept design of building envelopes has been explored in the past (Zemella & Faraguna, 2014), and in principle a large amount of design criteria could be combined in the process to define a fully quantitative optimized design. On the other hand, such an algorithm-driven approach requires a substantial effort for the definition of weighs to combine the different design criteria, and this is not always possible to address. A lighter, more intuitive way of informing the decision process is preferable as it reduces the barriers towards a truly holistic design, which is the final target of a design team (Arup, 1970).

The following sections will explain in detail how the different levels of information are calculated. The opportunity of considering all these aspects at the same time and in an interactive and user-friendly way are key for the quality of the information provided and hence the likelihood that the design team can use this information to drive the design efficiently.

2.1 SOLAR ASSASSMENT

Cooling and on-site energy requirements are typically defined based on energy saving strategies, regulations or certifications to gain. During early design phases, for example, a mechanical system can be identified suitable to achieve specific sustainability goals. For example, low energy systems such as passive chilled beams or displacement ventilation can be identified as viable options to cope with solar gains or specific targets of renewable energy production can be preliminary established to offset peak or annual demands. A review of the tools currently available to assess building performance showed that there is a lack of methods that provide enough flexibility to deal with the lack of detailed information and the need for agile changes typical for the early design stages (Negendahl, 2015).

The authors of the paper developed Arup Solar - a Radiance-based application developed in Unity (by means of C#), a well-known videogame engine (Donato, Zemella, Rapone, Hussein & Black, 2017). The tool, validated against other calculation methodologies, evaluates the incident solar radiation on a mesh distributed along the envelope of a building by using the Radiance Monte Carlo backward raytracing approach. The data is then post-processed. The application requires a geometrical input (for example Rhinoceros) and a simulation environment where solar analysis can be performed and the standalone application created (for example Grasshopper) - Fig. 1.

The tool aims at investigating the relationships between envelope features (e.g. window to wall ratio, g values, shading design, etc.) and cooling strategies, as well as identifying potential opportunities for renewable solar energy production – both photovoltaics and solar thermal.

Its standalone nature helps a seamless and effortless choice of the main building passive and active strategies towards sustainable buildings since the very beginning of the project when the potential impact of design decisions is at its most.

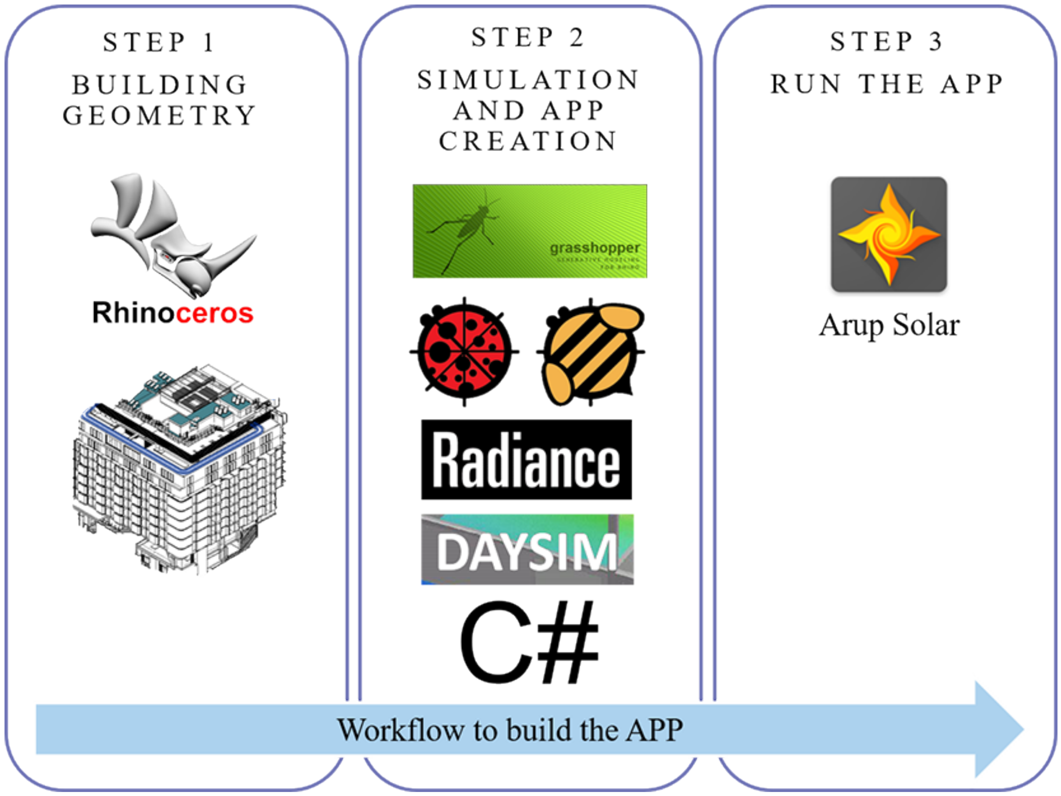

FIG. 1 Workflow to build an Arup Solar model

2.2 VIEW ASSESSMENT

Assessing the available views from a building requires both a quantitative evaluation of the number of visible points of interest and a qualitative description of such views. In order to address both aspects, the assessment has been subdivided in two parts: firstly, the % of points of interest visible from any areas of the façade was calculated and then the actual view from any test point of the façade was visualised.

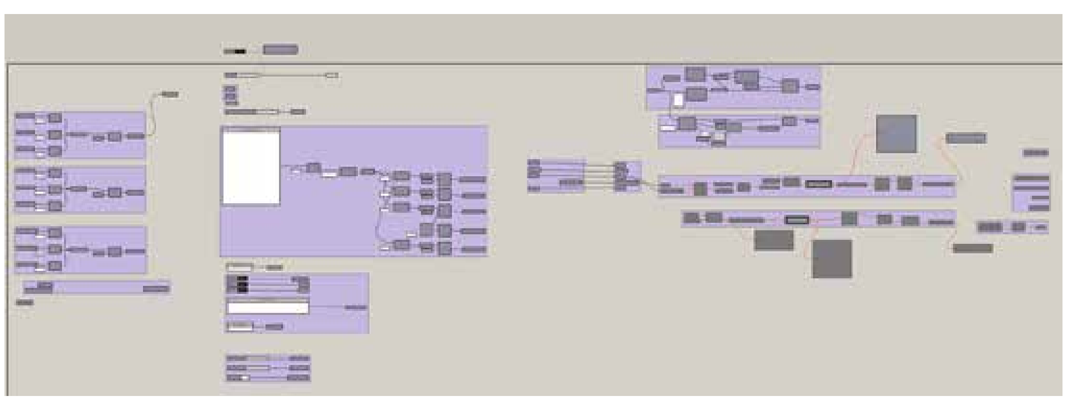

FIG. 2 Grasshoper script to determine the available significant views

The first analysis is carried out by means of Rhinoceros and Grasshopper (Fig. 2) where an ad-hoc script uses the ray casting technique (Roth, 1982): this process shoots an invisible ray from the test point of the façade in the specific direction towards the point of interest. If the ray detects any colliders laying in the path towards the target, the corresponding point of interest is disregarded.

Ray casting should not be confused with ray tracing (Larson & Shakespeare, 1998) where the ray is not computed only once but in an iterative way to assess any reflected or refracted light.

The visual outcome of the simulation is a 3D false colored envelope where two data can be visualized:

- % of points of interest seen from a specific point;
- A weighted score for each test point of the façade assessed.

While the first data are objective, the second data are subjective where the Client, the Lead Designer or the Design Team define the criteria and the weight of each point of interest:

$$Score = \sum_{i=1}^{n} \alpha_i \cdot \beta_i = \sum_{i=1}^{n} \alpha_i \cdot \left(\frac{\gamma_i}{\sum_{x=1}^{n} \gamma_x}\right) \cdot 100 \; [-]$$

Where:

- α_i, is a "boolean" operator, "1" if the point of interest is seen and "0" if not;
- β_i, is the "weighted weight" for each point of interest – the sum of every β_i gives "100";
- γ_i, is a generic weight given by the Client, the Lead Designer or the Design Team to the specific point of interest. It can be any number;

For this assessment, the % of points of interest seen from a specific point is considered.

The second analysis is carried out in Unity (by means of C#) with a tool that enables to visualize from any point of the façade the expected view, Arup Panoramic. The application is lightweight and it can be integrated in Arup Solar so that all the results are embedded in the same tool. The workflow is simpler than the one for creating an instance of Arup Solar and presents just two steps – from the geometry of the building and the surroundings, Unity generates the different views.

The application provides 360 degrees views from any points of interest and in the future could also provide instantaneous and integral numerical results for anything seen.

3 EXPERIMENT

3.1 DESCRIPTION OF THE EXPERIMENT

The methodology described in the previous section has been applied during the concept design of a large development that includes a residential tower (~50 storeys) surrounded by lower commercial buildings. Different massing options were considered during the feasibility study of the project, and one of the key decisions was the orientation of the residential tower, which had to take into account the following aspects:

- Implications on the daylight levels on the apartments;
- Amount of direct sunlight on the roofs of the lower buildings which are intended to become public spaces;
- Availability of key views from the apartments.

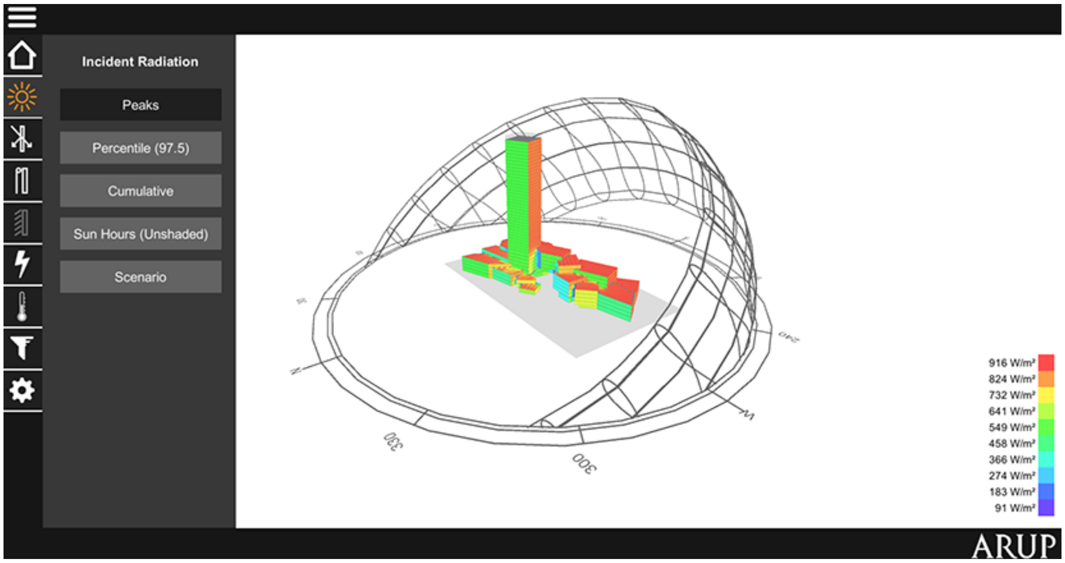

FIG. 3 3D model of the project – screenshot of Arup Solar (context turned off)

An Arup Solar model for the different options considered could answer the first two points (the functionality of calculating the vertical sky component was added in this occasion). For the client it was very important to understand if a different orientation of the tower could lead to a higher level of viable views from the different apartments, as this is a key consideration for the definition of the commercial value of residential units. The methodology described in section 2.2 was implemented. One of the requirements for this assessment was that the results had to be very easy to read and understand so that they could be interrogated by the different parties during a workshop.

3.2 DEVELOPMENT OF THE TOOL

Given the lack of a tool that could combine all the necessary information in a visual and simple way, it was decided to develop a project-specific instrument that would allow the design team to make an informed decision at the end of the feasibility study.

For each orientation of the tower there was the digital model providing information about solar gains and potential for daylighting and the assessment to quantify the number of viable views from the different parts of the tower. All this data was combined in an interactive 3D model in Unity, so that the information could be easily available and understood. Simple screenshots of the different tower positions allowed the team to compare the scenarios considered and to decide the final position of the tower.

4 RESULTS

The images in this section summarise the results of the assessment and provide an example of how the tool can be used. The first comparison between the three considered orientations of the tower refers to the Vertical Sky Component (VSC). Arup Solar plots on the elevations contours subdividing the building envelopes into the following areas (BRE, 2011):

- VSC ≥ 27%, where conventional windows are expected to deliver good levels of daylight in the interior spaces;

— 15% ≤ VSC < 27%, where design measures are needed to achieve good daylight levels;
— 5% ≤ VSC < 15%, where it is considered very difficult to achieve good daylight levels;
— VSC < 5%, where it is not possible to achieve good daylight levels.

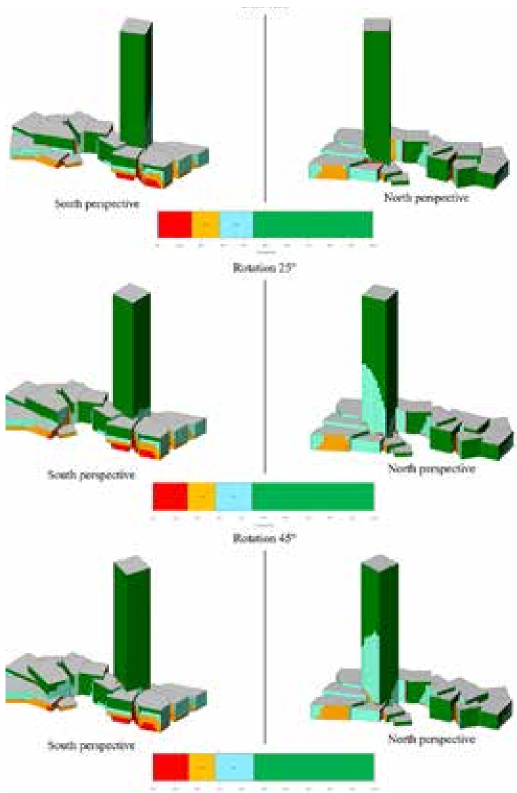

FIG. 4 Levels of VSC across the development (context turned off)

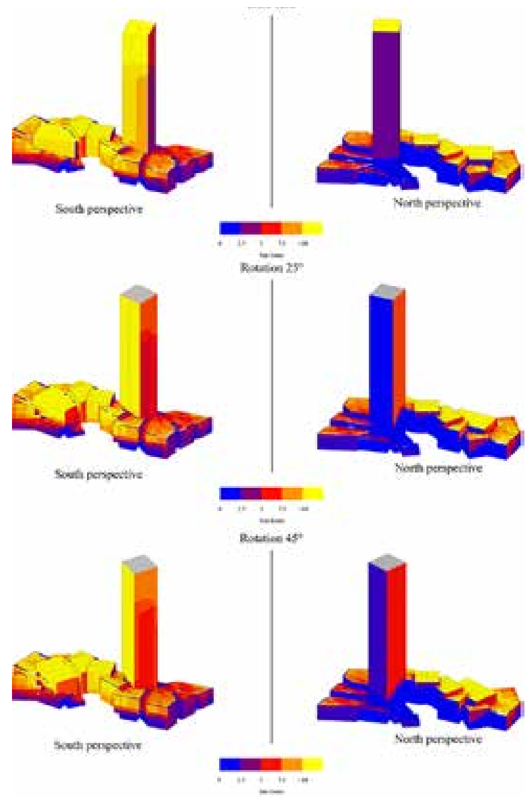

FIG. 5 Distribution of sun hours during mid-season across the development (context turned off)

The following considerations can be drawn:

— All three options lead to ~70% of the development having a good / reasonable level of daylighting (~55% will be fine with normal-size windows, ~15% will require some design measures);
— If we focus on the tower, the base case and the 45° rotation achieve very good daylight everywhere, with only some design challenges on the north-east elevation. The 25° is slightly worse.

In order to understand the availability of direct sun on the public spaces of the development, it was decided to evaluate the expected number of sun hours during the mid-seasons (i.e. spring and autumn). Discussions with the landscape consultant defined to target at least 7.5 hours of direct light per day, as in this way there would be a wide range of options for the selection of plants on the development.

As it can be seen from Fig. 5, there are no significant differences for the considered options, even if the scenario with the tower rotated by 25° is slightly worse than the others.

In terms of viable views from the residential tower, the results of the analysis have been plotted on the elevations showing the % of interesting views available from each area of the façade. As it can be seen from Fig. 6, the option where the tower is rotated by 25° is the one that leads to the maximum number of views.

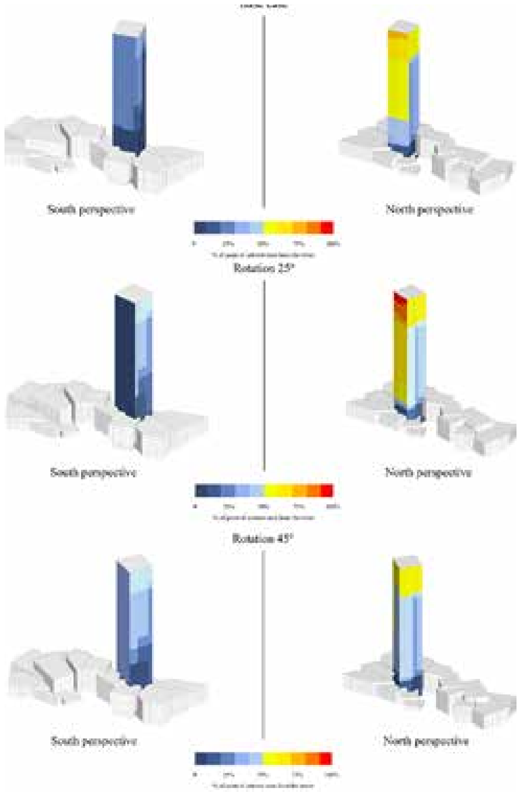

FIG. 6 Distribution of available significant views from the residential tower (context turned off)

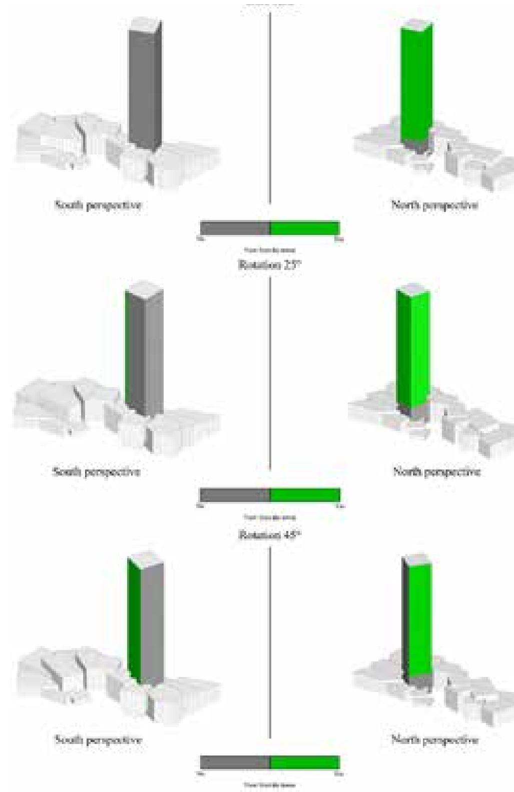

FIG. 7 Availability of the most viable view (context turned off)

Such a quantitative way of measuring the availability of views has obvious limitations, the main ones being:

- Not all the significant views have the same level of importance. It would be good to identify the areas from where the most viable view can be seen;
- Even if it is good to know that a specific landmark can be seen, it is also important to know the quality of such a view.

The first limitation was overcome by plotting on the tower elevation the availability of the view the was considered most important, as shown in Fig. 7. This could be extracted from the visual tool simply by clicking on the relevant button. As it can be seen, when the tower is rotated by 25° an additional strip of façade can access the selected view.

In order to give a good and timely opportunity to visualize the quality of the view from each part of the building, an ad-hoc tool was developed: Arup Panoramic. The tool allows the user to navigate across the model of the project, click on any module of the external envelope and visualize what an occupant could see from there. Figures 8 and 9 show the tool. Since the project described is confidential, figures 8 and 9 refer to the theoretical case of the project being located in Venice.

FIG. 8 Screenshot of Arup Panoramic

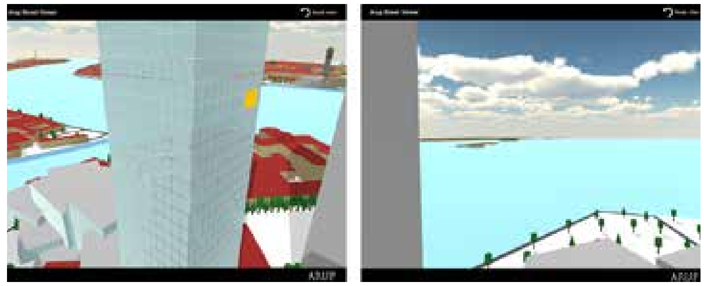

FIG. 9 View (right) from the selected facade area (yellow, left)

The results of these assessments were all embedded in the Unity visualizer and were discussed during a workshop with the different members of the design team and the client. The opportunity of considering at the same time performance criteria and the view assessment allowed to have a debate about tradeoffs between energy efficiency, well-being and value of the building. It was decided to have the tower rotated by 25° and accept some compromises in terms of daylight and direct sun availability across the whole development, in order to maximise the views from the tower.

Apart from the specific considerations applicable for the project presented, a recurring question is about the opportunity of quantifying the tradeoffs between the different criteria, which involves a multi-objective optimization process. This is possible, but the main difficulty would not be the implementation of the tool itself but rather the pre-definition of weights to be assigned to the different criteria. The approach presented in this paper leaves this process more qualitative: even if this has some limitations, it can be understood and managed by a number of different parties.

5 CONCLUSIONS

This paper has presented a new digital tool that combines performance-based assessments (such as daylight availability, solar gains, potential for on-site energy production) with an evaluation of the availability of views. This tool was developed to meet requests from developers and architects who need more support during the early design stages, as this is when key decisions can have a very significant impact on the value of a development. A case study showed the potentials of the tool and how this can be used to inform the design.

It is not straightforward to combine quantifiable aspects with more qualitative design criteria and this tool does not provide a final answer whether one concept design for a building is better than an alternative option. The purpose of the digital tool is to give the opportunity of considering all the relevant criteria at the same time.

The following steps will be focused on making direct comparisons quicker and simpler, without compromising the ability of the tool to adapt to the specific requirements of the different projects.

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Auxetic Structures and Advanced Daylight Control Systems

Abstract Only! Full Paper in JFDE 2019.1

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Abstract

Building envelopes in general and, in particular, fenestrations are the places in which most interactions between indoor and outdoor environment take place. As a result, an effective shading structure for windows, which can provide sufficient illuminance levels and at the same time ensure acceptable visual comfort by controlling the glare is highly desirable.

Static daylight control systems are mostly designed to either completely shade the façade from sunlight or admit and re-direct it to the indoor spaces. Dynamic control systems adjust the amount of intake sunlight with assistance from users or mechanical devices. Studies to date have not thoroughly and comprehensively developed an alternative system in which a self-morphing structure that is responsive to outdoor environmental conditions can function as an "adaptive daylight control system".

This paper has investigated the effects of the adaptable auxetic shading structure with varying geometries to optimise illuminance levels and reduce probability of glare. The paper developed a model to be tested in various locations in the U.S., to evaluate the illuminance and glare performance. The results suggest that the auxetic shading structure can effectively block sunlight from entering the space by adjusting its geometry in response to varying outdoor and sky conditions. In addition, a strong correlation can be concluded among daylight availability, sun exposure, and glare probability.

Additionally, the optimisation of daylighting parameters such as illuminance and glare show a clear correlation between the location of the case study and its corresponding sun angles, and the performance of the shading structure. Future studies may explore the effect of auxetic shading structures on energy consumption and thermal comfort parameters. In addition, the relation between auxetic shading devices and the health and well-being of building occupants may be another factor to be considered in the evaluation of effectiveness of this new generation of shading devices.

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The PLUG-N-HARVEST Façade: A Second Skin with Active and Passive Components

Abstract Only! Full Paper in JFDE 2019.1

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Abstract

The construction of office buildings in particular, as well as multi-family dwellings, are largely based on regular planning grids, and the widths of such grids appear to be repetitive across Europe.

In the EU project, PLUG-N-HARVEST, a multi-modular façade system for refurbishment, based on these planning grids, is developed. To achieve a comprehensive improvement of the building´s energy efficiency, different solutions for active and passive energy demand reduction, as well as harvesting of heat and power were combined, while also taking into account the existing building structure, climatic region, and usage profile.

The PLUG-N-HARVEST facade is designed to enclose the existing facade like a second skin. Thus, the remaining protection provided by the existing outer shell allows the continued use of the building during retrofitting measures. At the same time, its conservation reduces the need of embodied energy.

Pilot projects in Greece, Spain, the United Kingdom and Germany will be used to validate the technical implementation of the PLUG-N-HARVEST concept and to assess its ecological and economic benefits..

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Impacts on the Embodied Energy of Rammed Earth Façades During Production and Construction Stages

Abstract Only! Full Paper in JFDE 2019.1

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Abstract
Rammed earth is a technique for constructing sustainable buildings, with a low energy demand encompassing the whole life cycle of buildings. Soil from the excavation can be compressed on-site to build a façade. Due to its hygroscopic and thermal properties, rammed earth façades stabilise indoor comfort, which potentially supports the minimisation of use of mechanical systems. In order to reduce the energy demand for the entire life cycle of buildings, the embodied energy must be taken into account. Databases, such as the German Ökobaudat, provide data for a life cycle assessment (LCA). For rammed earth, aggregated data at product stages A1-A3 are provided, but transport, which is included in stages A2 and A4, and construction processes at stage A5 are barely documented. Thus, the energy demand for transport, production, and construction of two rammed earth façades was measured. The results are documented in this paper, which provides a more thorough understanding of the entire building process and helps to expand the database. One can conclude that transportation has the largest impact on the embodied energy of rammed earth façades, so it's essential to use local material. Furthermore, the results illustrate the implication of transport on a life cycle assessment, as well as for other constructions.

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Comparative Overview on LCA Software Programs for Application in the Façade Design

Abstract Only! Full Paper in JFDE 2019.1

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Abstract

Façades impact the environmental performance of a building by their passive contribution to operational energy demand and by embodied energy and emissions during each life cycle phase. LCA is a method widely used to quantify the environmental contribution. The use of LCA software programs in façade planning can guide design decisions and contribute to environmental optimisation.

A large amount of LCA software programs have been developed so far, all of which differ in their focus and requirements. This paper aims to address these differences and investigate the capability and suitability of these programs for façade design. It is structured in four sections. The first part introduces LCA in the building and façade design context. The second part introduces categories to understand the different capabilities of LCA software products. Hereafter, eleven products are evaluated based on these categories. The fourth part focuses on the suitability of software products for simple or complex façades.

The study concludes that there are different software choices available for almost every level of user knowledge. While Gabi, Simapro, and Umberto require users to work to a high level of proficiency, software programs like eLCA, CAALA, and 360 Optimi do not require much user knowledge over LCA, but provide a range of other opportunities.

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SMP Prototype Design and Fabrication for Thermo-Responsive Façade Elements

Abstract Only! Full Paper in JFDE 2019.1

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Abstract

The aim to attain sustainability in the built environment introduced the innovative application of advanced material technologies for low-energy, but aesthetically intriguing, building design strategies. Adaptive and responsive building skins as embedded and intrinsic control systems can be delivered with smart materials, and thus have the potential to minimise the energy consumption of buildings by maximising the natural and passive adjustment of façade components for shading, air-flow, daylight, and view. The dynamic smart material façade, adaptable to changing outdoor environments, is considered to be a holistic design approach that integrates the behavioural performance effects with the appearance and aesthetics of kinetic ability provided by smart materials acting as actuators, by adjusting their properties according to external stimuli.

Of the various environmental inputs sensed by, and actuating, active and dynamic building façade systems, this research focuses on temperature as the stimulus to activate a dynamic shading device with the mechanism of opening and closing, specifically considering Seoul's climate. Among currently available thermo-responsive smart materials, the shape memory polymer (SMP) is investigated as an activator of shading devices to be implemented to adaptive building skin strategies. As the first stage of SMP prototype design and fabrication study toward the thermo-responsive building façade elements, SMP prototypes are proposed in cell types.

Among the general thermo-mechanical cycle of thermo-responsive SMP, only programming of the permanent shape via additive manufacturing and recovery at the activation temperature are focused upon in this research. This study proposes a design-to-fabrication workflow integrating computational tools, 3d printing and recalibration of relevant variables in digital design process, G code generation, and manufacturing using commercially available SMP filaments. To verify the 3d printing process, and to demonstrate the shape-changing behaviour of SMP actuators, reproduction of a referenced prototype was conducted, in addition to fabrication experiments of SMP surfaces with various thicknesses and SMP hinges with customised rotating angles.

In addition, a base-line prototype combining the static ABS plate and the active SMP hinge is developed to set up the heat test and a digital motion simulation from data of shape changing behaviour acquired from a hands-on model test. After the demonstration of the baseline prototype in design and additive manufacturing process, various SMP prototypes were designed with reference to kinetic prototype researches, but with the consistent 100mm-diameter circular surface, in a scale of 1:3. They were also fabricated with a 3d printer for both open and closed positions to testify to their constructability, and thus to comparatively evaluate the design and fabrication outcomes. Furthermore, after conducting radiation and thermal simulation analysis, shading performance validation is noted for selecting potential prototypes. Lastly, the needs to further develop reversible reiterative shape-changing materials or systems are briefly discussed.

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PART 2 // ENVELOPE

4D adaptive textile building skin

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Abstract

Current applications of architectural fabrics as second-skin facades are predominantly used as rigid systems lacking the ability to regulate visibility and solar impact. In contrast to the construction industry, other branches are far more advanced with regards to the implementation and individualization of smart textile technologies.

In a joint research project with an interdisciplinary team of building experts from research and industry, the faculty of Architecture at RWTH Aachen University is closely collaborating with the RWTH Department of Textile Engineering (ITA) and the RWTH Clinic for Ophthalmology as well as different international partners from the textile industry, whereas collaboration involves teaching, research, and application-oriented realization. So far, the research group has set up the conditions for the development, analysis and evaluation of novel facade prototypes. The requirements for the new prototypes can be summarized as follows:

- *Auto-reactive adaption regulating visibility and solar impact without dislocation of the fabric*
- *Large-surface homogeneity*
- *Ability for user-dominated intervention*

In this work, we present the results of our 4D auto-reactive design study. For auto reactive systems so called 4D Textiles are researched, wherein the 4th dimension is the change of shape and/or functionality over time.

The underlying concept behind these hybrid material systems is to store energy in the textile material prior to printing and then release that energy to affect form and function of the hybrid system. Typically knitted fabrics that contain elastic material are used due to the high elastic strain available and sufficient recovery force. The material should be highly deformable, but still maintain a reasonable tensile modulus. After printing the stored energy is released which leads to a structural change in the system, generally changing form from a 2D printed structure to a 3D curved structure. When properly designed, it is possible to make a 3D structure that is metastable, and thus able to assume two or more different stable structural forms that can be switched back and forth with nominal energy applied.

In future auto-reactive facade elements can be designed based on the materials developed at ITA, that change their pore structure or macroscopic shape due to external stimuli or electric triggers by the user. With a change of the permeability of 4D textiles can for example be used for sun protection in summer and as an isolation material in winter time due to temperature changes.

Keywords

4D textile printing, adaptive facade, auto-reactive facade, architectural fabrics, digital building skin, energy efficient architecture

6 INTRODUCTION

6.1 AREA OF RESEARCH – ADAPTIVE TEXTILE BUILDING SKINS

The Aachen research group "Adaptive Textile Building Skin" deals with the concept of creating the greatest possible transparency with novel facades to maximize the link between indoor and outdoor space and at the same time provide sun protection, intimacy and an aesthetic appearance. The desire to create highly transparent buildings has long been an aspiration in architecture and engineering. Large-format efficient glazing with minimal frames is increasingly characterizing the facades of modern buildings (Sobek 2014: 506-517). Highly transparent buildings have been built worldwide for many decades, especially in the areas of office and administration buildings. Built examples range from the Chrystal Palace in London by Joseph Paxton and the Bonn Post Tower by Murphy & Jahn in cooperation with Heinle Wischer & Partner to the recently built Apple Campus in California by Foster & Partners.

Nowadays, energy efficiency is a crucial aspect in the building sector, not only because of the distinctive construction norms and standards. Especially in Germany, particularly high demands prevail on the energy requirements of buildings due to the significant impact of buildings on global energy demand and CO_2 emissions [United Nations 2010]. At the same time, there is also a growing sensitivity in society about dealing with energy needs and alternatives for power generation. Increasingly high demands are posed on the building skin, its built-in materials and the technology used for flexible solar protection and air conditioning. Thus, the development of novel building facades is increasingly focusing on convertible and intelligent systems [Heusler]. In this context, textile facades offer a number of advantages. On the one hand, they serve to improve the energetic and climatic performance of the building envelope, since the textile building skin serves as a solar protection element that prevents the building from heating up during the cooling season [Werwath]. On the other hand, textile facades belong to the increasingly popular group of large-area homogeneous diaphanous facades. Diaphanous facades are characterized by secondary facade elements located outside of the primary facade layer. Built examples include the Thyssen Headquarter in Essen, Allianz Arena München and Messe Basel by HdM, and the New York Times Building by Renzo Piano. Some projects include movable facade elements that are controlled via a building automation system (Al Bahr Towers by Aedas) others include rigid elements that are permanently visible from the inside and outside. Experimental studies prove that inhomogeneous indoor lighting conditions can reduce the concentration of employees and therefore efficiency [Bernges], [Lang].

During daytime, textile facades are almost unnoticeable and allow an almost unrestricted view from the interior to the exterior – their structure resembles a transparent veil. Due to the daytime lighting situation (dominant ambient light), textile facades have a sculptural appearance during the day (Fig. 1). From the outside, one cannot see whether there are opaque or transparent surfaces behind the textile elements – the usual distinction between wall and opening is no longer present. With the reversal of the lighting situation, the artificially illuminated building interior begins to shine outwards during the evening hours. Persons who are in the building at this time can be recognized from the outside. Especially in residential buildings, this effect has to be taken into consideration in order to adjust the degree of transparency of the textile to a level, where only silhouettes are seen from outside.

a) Maximum transparency

b) Medium level of transparency

c) Low degree of transparency

d) Variable degrees of transparency

FIG. 10 Visualization of exemplary building with an Adaptive Textile Facade. Influence of building skin on overall appearance

Intelligent materials that enable auto-reactive state changes in analogy to natural principles enjoy a rapidly growing popularity, as many system manufacturers have confirmed. At the same time, there is still a great need for research in this area [Mitterer p.11]. For almost thirty years similar technical textiles have been used for textile facades. The Aachen research group consisting of ITA, the Faculty of Architecture and UKA, aims at developing a membrane which is eventually characterized by the following properties: large surface homogeneity (1), adaptivity (2), autoreagibility (3), and fixed position (4). The textile facade elements are developed so that they can independently register environmental conditions and adapt the system transparency with regards to the light and visual transmission. For this research goal, the interdisciplinary research team has been growing since 2016 and is actively carrying out experimental research in this area. One major research focus is the connection between energy and design. Besides the characteristics of smart materials, we aim to include user dominant control to realize a flexible interaction between indoor and outdoor environment and that way enhance individual user comfort. That is why different types of smart materials, such as shape memory polymers, metals and bimetals were researched.

6.2 INTERDISCIPLINARY RESEARCH TEAM

The RWTH Aachen University Faculty of Architecture has been continuously conducting seminars on the development of adaptive textile facades since 2016. The seminars are attended by students from both the Faculty of Architecture and the Department of Textile Engineering (ITA). The close collaboration with the ITA and partners from the construction and textile fabrication industry, allows a profound exchange of expertise in the field of innovative technical textiles as well as a fast and timely realization of textile prototypes and samples in the RWTH test laboratories under high-end conditions.

Within the joint research, the Faculty of Architecture focuses on concept, design and structural development as well as 4-dimensional motion sequences and the specification of material requirements. The ITA is responsible for consulting and the technical implementation of respective concepts and carries out the technical innovation analysis in the RWTH laboratories. An additional aspect of the joint research is the perception of membrane structures with regards to the human eye. Therefore, the RWTH Faculty of Architecture also collaborates with the RWTH Clinic for Ophthalmology to evaluate the influences on the perception of membrane structures in the human field of vision (Fig. 2). Ongoing investigations deal with the influences of geometrical principles, colorfulness, degree of opening and viewer perspective and distance to the examination structure.

7 METHODOLOGY

To lay the groundwork for the investigations, fundamentals were researched for material development, manufacturing of technical textiles, characteristics of human vision, and properties of different auto-reactive actuators. Furthermore, requirements of the facade with regards to building laws, climatic conditions and user behavior (e.g. in residential vs. office buildings) were defined.

At the beginning of the investigations, medical scientists and architects combined their competencies for an experimental series of "perception and structure", i.e. how different types of textile structures are perceived by the human eye under various conditions. Therefore, a visual test procedure was developed and carried out with significant number of test persons. In the second step, architects and textile engineers worked together to develop concepts and designs for a broad range of functional principles. Various combinations of textile structures and smart materials were used to carry out auto-reactivity tests in the RWTH lab environment. Eventually, prototypes were constructed at 1:1 scale as representative excerpts of a large-surface textile facade. Ultimately, the Faculty of Architecture and the Department of Textile Engineering (ITA) are planning to construct a full-scale demo facade for detailed measurements under real-life conditions.

On the one hand, evaluation and optimization of the different concepts is carried out by scientists from ITA, the RWTH University Hospital and the Faculty of Architecture. On the other hand, experts from the construction industry as well as clients and building-owners give valuable input for an assessment of the innovative concepts.

8 RESEARCH & EXPERIMENTS – 4D ADAPTIVE TEXTILE BUILDING SKIN

8.1 INVESTIGATIONS ON "PERCEPTION & STRUCTURE"

In the age of decreasing privacy, the domestic environment has to be protected in particular. The boundless view into nature is often paid with missing intimacy. It's an important part of building technology to create a protective atmosphere by keeping structural transparency and lightness at the same time. The knowledge of affecting parameters as well as the highly complex system of the human eye makes it possible. The photoreceptor cells of the retina convert light stimuli into

FIG. 11 Interdisciplinary RWTH research group

electrical signals that are referred over optic nerves to the visual cortex. Thereby, optical operative ingredients of the human eye like cornea, crystalline lens, aqueous fluid and the vitreous body are caring for a maximum sharp picture on the retina. Besides the acuity of vision, contrast, color and movement viewing as well as the field of vision influence the visual impression significant too. Illuminating these factors is incumbent upon the collaboration of architects, building technologists and oculists. In the age of decreasing privacy, the domestic environment has to be protected in particular. The boundless view into nature is often paid with missing intimacy. It's an important part of building technology to create a protective atmosphere by keeping structural transparency and lightness at the same time. The knowledge of affecting parameters as well as the highly complex system of the human eye makes it possible. The photoreceptor cells of the retina convert light stimuli into electrical signals that are referred over optic nerves to the visual cortex. Thereby, optical operative ingredients of the human eye like cornea, crystalline lens, aqueous fluid and the vitreous body are caring for a maximum sharp picture on the retina.

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The contrast sensitivity for example plays a major role in observing lattice structure, spatial position and size and form of objects. Contours, patterns, edges and outlines are only getting visible due to contrasts in the brightness. In front of a bright background, a grey surface appears much darker than in front of a dark background. The decisive factor in this respect is the organization of the retina by receptive fields, the distribution into On and Off-Center neurons. A prominent example for that optical illusion is the "Hermann Grid". While watching that grid, a black spot will be recognized at the white intersections of the lattice. By fixation of the intersection, the black spots will disappear. This phenomenon is described as "lateral inhibition" in most of the physiology textbooks [1]. However, the previous interpretation is probably incomplete. An irrelevant modification of the grid in form of a waviness of the gridline terminates the brightness illusion. A declaration for this fact was made in 2007 based on an artificial neural network, which "learned" brightness constancy [2].

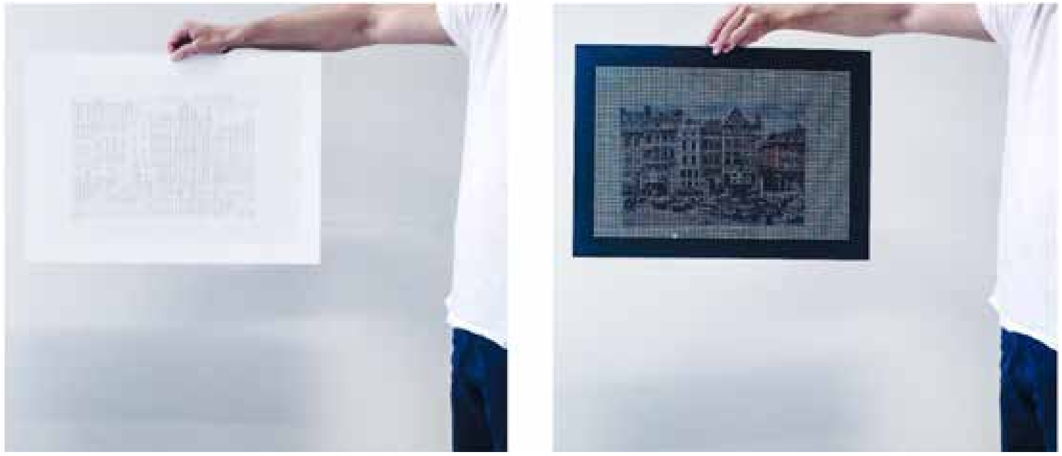

FIG. 12 Influence of color and contrast on perception. White and black plates with similar structure (10 % opening degree), but different color schemes show the different levels of contrast

The ability to interpret differences in brightness according to the object recognition correctly, regardless of the lightning, is described as brightness constancy [1]. This is another field of research opening up. This phenomenon is just an example for the complexity of visual perception. The test for studying the visual properties of textile membrane facade designed by us is based on standard research methods of the ophthalmology. In different series of seminars, the basics of visual perception, contrast and color viewing were taught to students of architecture. Due to the gained knowledge, the decisive influencing factors were determined in common for our experimental setup. The testing of spatial resolution as well as the contrast viewing are the two fundamental aspects. Before starting the test, a binocular visual test has to be made. Even a significant reduction of eyesight is a general elimination criterion for the test participation.

For testing the effect of the virtual membrane facade on the spatial resolution as a quality of vision, elements of the textile membrane facade are set between proband and the EDTRS board in a defined distance. The EDTRS board deals with a globally recognized basic test to determine the spatial resolution. The study participants are asked to appoint standardized optotypes correctly. To simulate the use of textile building skins in the daily routine, it's conceivable presenting video sequences instead of optotypes to the proband. The use of these video sequences allows to represent temporal resolution according to motion perception and to test the impact of the facade on it. Furthermore the deployment of modern, cost effective and flexible virtual reality which simulates the extensive use of the textile facade under test is planned. Psychological aspects do have an impact on the whole perception as well. Phenomena like the law of proximity or aspects of color perception such as the phenomenon of color consistency are decisive factors.

For testing the impact on contrast sensitivity a contrast sensitivity test referred to Pelly Robson will be carried out (Fig. 3). Crucial criteria besides the size of the optotype to be recognized are ambient lightning, illumination of the board and the distance of the proband to the membrane as well as the distance of the membrane to the board. The test is done repetitively with different perforations of the membrane and different perforation patterns (circular, linear, regular and irregular). In addition, the elements of the membrane facade are reviewed in different colors and different color saturation. The surface quality is varied as well: matt, glossy, 3D structure etc. (Fig. 4).

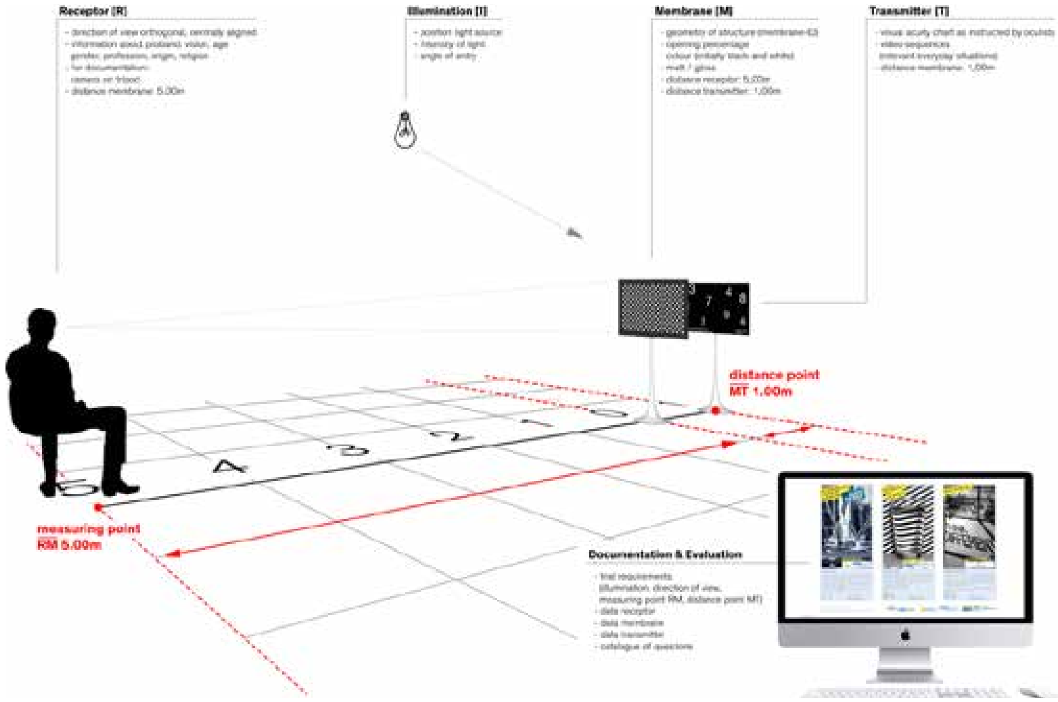

FIG. 13 Sensitivity test developed to investigate the influence of structure on perception

8.2 EXPERIMENTAL 4D PROTOTYPE CONCEPTION

The RWTH Department of Textile Engineering (ITA) headed by Prof. Gries and his scientific assistant David Schmelzeisen has been investigating 4D adaptive textile skins since 2015. 4D printing has been described by Ge, et al. as (Ge, Qi, and Dunn 2013):

"[...] active materials, such as shape memory polymers, can be printed to create an active microstructure within a solid. These active materials can subsequently be activated in a controlled manner to change the shape or configuration of the solid in response to an environmental stimulus. This has been termed 4D printing, with the 4^{th} dimension being the time-dependent shape change after the printing."

In 2013, Skylar Tibbits defined 4D printing as 3D printing with time as an added fourth dimension (Tibbits 2013). According to Pei in 2014 (Eujin Pei 2014), "4D printing is a process that creates multi-material prints with the ability to transform over time or special material systems that can change shape. Today, due to the constant development of the technology, 4D printing is defined as a targeted modification of 3D printed structures with regard to form, properties, or functionality." Some of the properties that can be considered as changing with time (the 4^{th} dimension) are stiffness, permeability, color and degree of water absorbency (Momeni et al. 2017). Over time, changes may take place in the other dimensions, e.g. color or space. These changes are caused by stimuli (Chae et al. 2015; Choi et al. 2015; Momeni et al. 2017) as moisture, light, and warmth, as well as combinations of all three. Sound, UV radiation, microwaves, in addition to chemical, electrical, and mechanical forces are further stimuli that may active a system (Choi et al. 2015). The resulting structure is able to achieve self-assembly, multifunctionality, and self-repair (Momeni et al. 2017).

Today the scalability of the structures is problematic, both in terms of their geometry and the effect to be achieved. Therefore, the Institute of Textile Technology (ITA) is working on the implementation of time-varying multi-material systems consisting of highly elastic textiles and additive manufactured smart materials. (Schmelzeisen et. al. 2018). One example is the interdisciplinary research project

"Intuitex" (2013 - 2016) at ITA (Prof. Gries), the Chair for Communication Science (Prof. Ziefle) and the Media Computing Group (Prof. Borchers) at RWTH Aachen University, which aims at using novel, intuitive methods of controlling smart home devices by means of sensitive smart textiles.

Textiles combine high strength, elasticity and drapability with low bending stiffness. At the same time, they can be produced in large quantities at low cost and in a highly individualized manner. These properties make them the ideal basis for 4D structures. Functionalisation with autoreactive material can take place during textile production at fibre, yarn and surface level or in subsequent finishing. In their research, ITA employees benefit from the entire process chain - from fiber production to the functionalized end product - of one of the largest RWTH institutes.

The first connection of 3D printing and knitted textiles to autoreagible multi-materials caused a sensation. Autoreactive surfaces that support the user in the automotive interior are the first prototypes. In future, the researchers see a multitude of applications for such multi-materials: In addition to the realization of the living body for BMW, active facade elements for buildings, self-acting implants for medical technology or components for soft robots are the subject of development projects.

In Schmelzeisen et. al (2018), a user-centered design methodology for 4D objects has been presented. The proposed method is divided into three phases based on Design Thinking: the Understand, Create and Deliver phase. Figure 5 depicts the methodology. Here it was applied for the first time in the field of architecture.

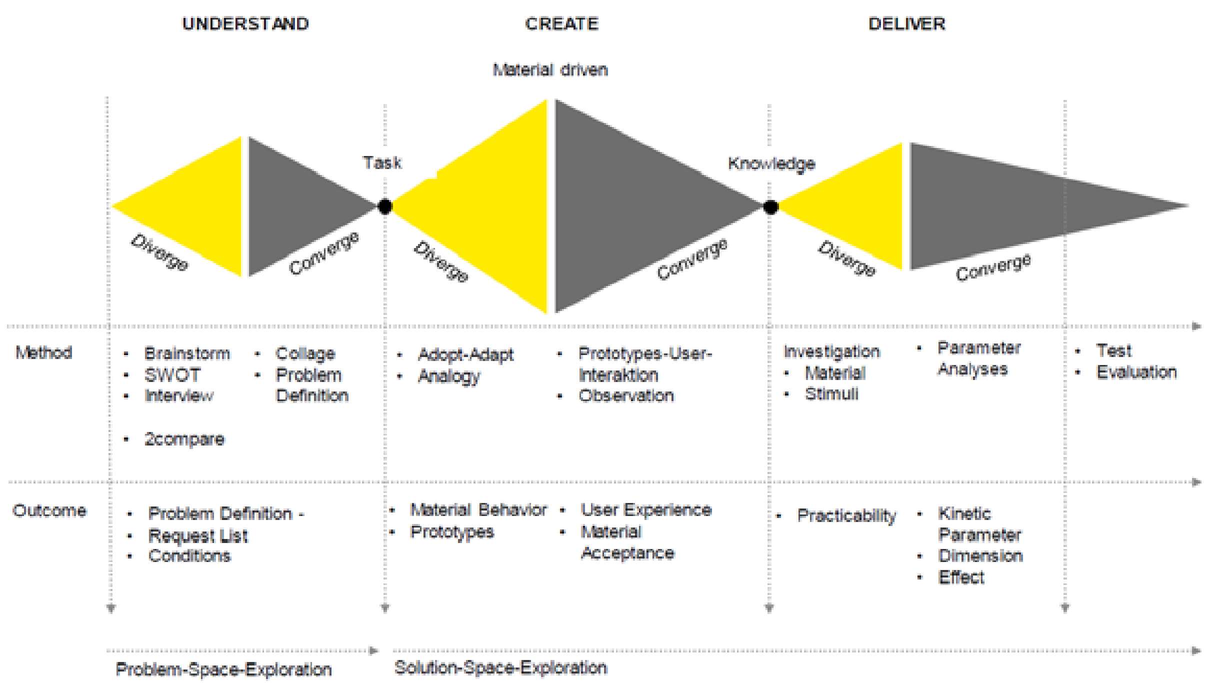

FIG. 14 User-centered design methodology for 4D objects

8.2.1 4D Prototype: HEX01 – Hexagon Facade (Fabric + SMP)

In the project "HEX01 – Hexagon Facade" (Fig. 6), thermoplastic polymers are used to close initially open hexagonal surfaces in the textile when the temperature exceeds a threshold of 60 °C. This is accomplished by a composite of the sensitive hexagonal surfaces with an elastic textile. Both materials are fixed on a carrier textile. In the course of the project so far, the design of the thermo-sensible hexagonal structure is primarily being researched. The hexagonal structure consists of thermo-sensitive hinges. In addition, non-thermo-sensitive elements connect the joints with each other, creating a closed hexagonal ring. The joints are formed by shape memory polymers (SMP) using the KO-BO filament by the Japanese company Kyoraku Co.LTD.

By means of a 3D printer, the SMP joint is printed in the desired shape, that the joint is supposed to resume when the temperature exceeds 60 °C ("memory shape") in the then softening state. Subsequently, the hexagonal surface is closed. To achieve a complete degree of closure, two joints facing (Fig. 6g-i: α,δ) each other must overcome an angular difference of 60° for each joint. At the same time, the other four joints (Fig. 6g-i: β,ε,δ,ε) move in the opposite direction and reach an open angle of 180° for each joint in the final position. In combination with the non-thermo-sensitive joints, the hexagon closes completely.

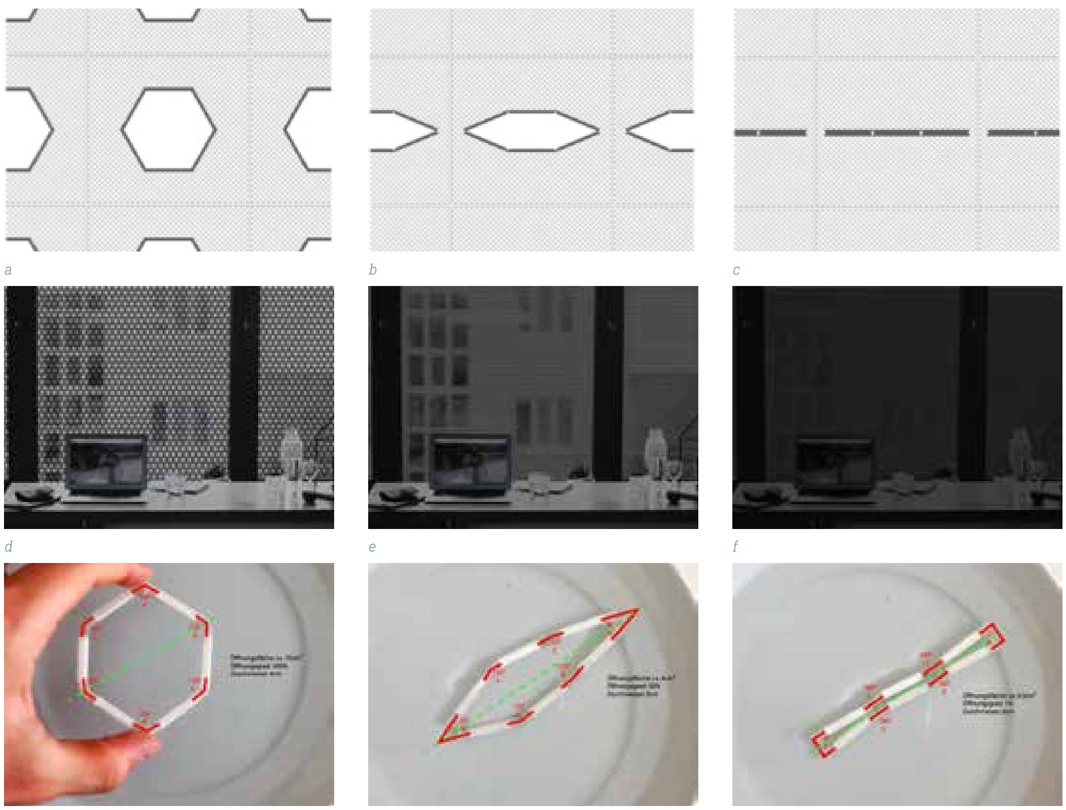

FIG. 15 4D Prototype HEX01 – Hexagon Facade (Fabric + SMP)

8.2.2 4D Prototype: SOL01 – Bimetallic Eye (Fabric + Bimetal)

In the SOL01 project (Fig. 7), thermo-sensitive bimetallic strips are used to stretch textile surfaces as the ambient temperature increases. Bimetals consist of two adjacent thin surfaces of different metals, which are connected in a form-fitting manner. For the purpose of this project, bimetal strips were woven into textile surfaces. The result is double concave (negative ellipse) and double convex curved (positive ellipse) frames. A linear textile substructure pierces through the textile composite element at three points. The puncture drill holes are carried out as long holes in order to allow tolerances. They are located on the outer face of the frame for the convex curved frames and at the frame center for the concave curved frames.

SOL01 uses thermally sensitive bimetals made of an active Iron-Nickel-Manganese alloy and a passive Invar layer. Due to a difference in the thermal expansion coefficients of these two metals, a change in temperature causes a bending of the bimetal strips. This bending is then used to actively change the transparency of the facade. In case of an increase in ambient temperature the strong temperature increase on the facade surface activates the bimetals causing them to expand and bend. This elongation is controlled by an individually elaborated frame, so that two opposite bimetal strips lying on top of each other cause a flexible textile to stretch in an oval shape. Through this process, the transparency within the facade can be regulated and nearly complete opacity can be achieved.

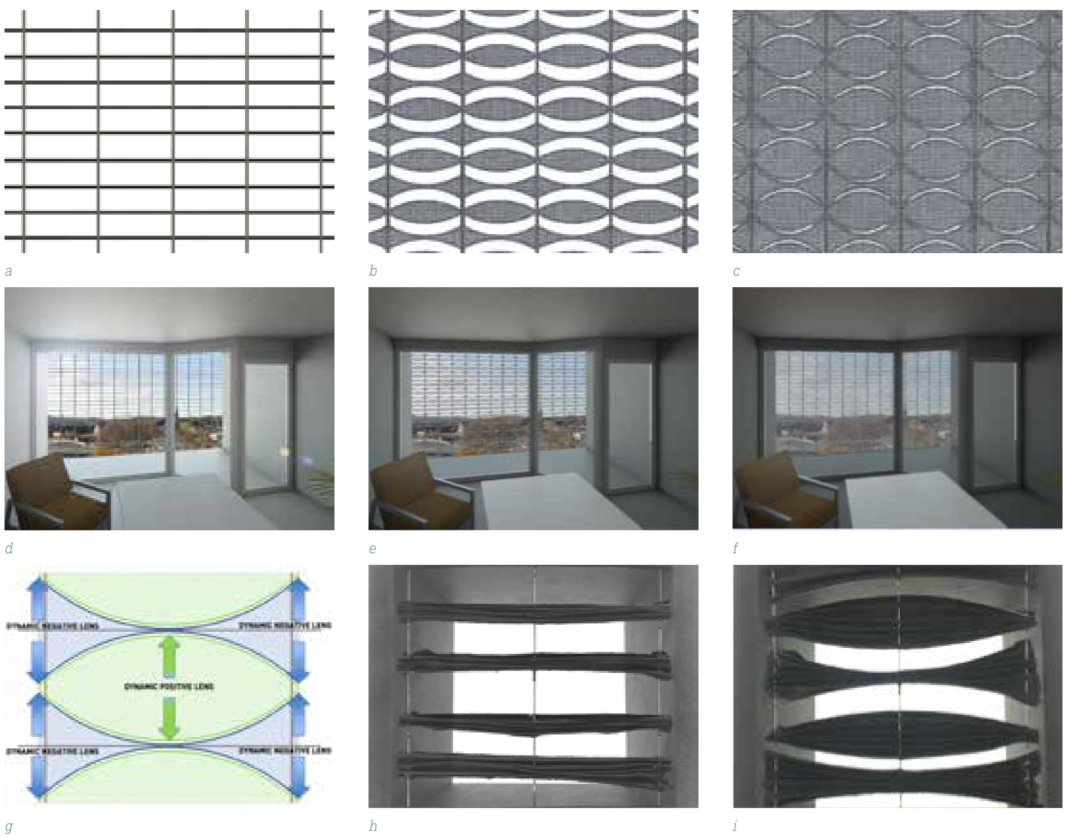

FIG. 16 4D Prototype SOL01 – Bimetallic Eye (Fabric + Bimetal)

8.3 4.2.3 POL01 - BIMETAL AND POLARIZATION (FABRIC + BIMETAL + MANIPULATOR)

The project POL01 (Fig. 8) uses coiled-up bimetallic springs to auto-reactively manipulate lighting and visual transparency of the facade depending on ambient and ultimately facade temperature. The “manipulators” consist of a pair of polarization filter foils with a polarization orientation of 0°. The polarization principle is based on filters that can regulate light transmission infinitely from 0-100% by turning the filters against each other. The circular shape of the polarizing filters allows a rotation about a common axis, and their symmetry allows the foils to always cover 100% of each other’s surface area. The first prototypes were quite complex in their design and consisted of multiple layers. Also, the number and size of the holding mounts in the disc area fixing the axis of rotation had a negative impact on polarization. Through numerous iterations supported by 3D printing of different configurations, an increasingly simplified element has been developed that is limited to the essential function.

The result is a textile that consists of individual interconnected circular elements. These elements consist of two outer polarizing discs, resting on a ring-shaped polymer. The inner polymer ring is 3D-printed and has integrated holes through which the individual elements can be connected to form a two-dimensional textile surface. Each polarizing disc consists of a polarizing foil and an external protection foil. The disc serves as weather protection and as a support for the rotation axis. Inside, directly behind the first disc the second polarizing disc is located. This inner disc can rotate by 90° and – in combination with the outer disc, allows the gradual darkening from 0 to 100%.

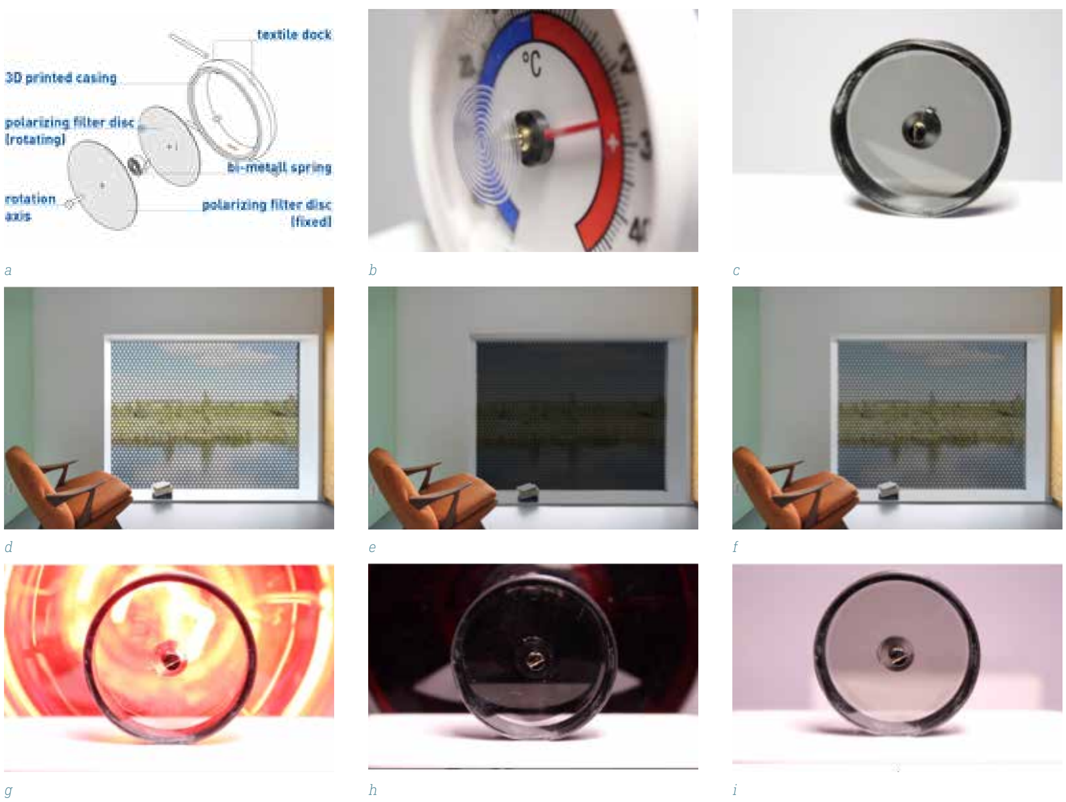

FIG. 17 4D Prototype POL01 - Bimetal and Polarization (Fabric + Bimetal + Manipulator)

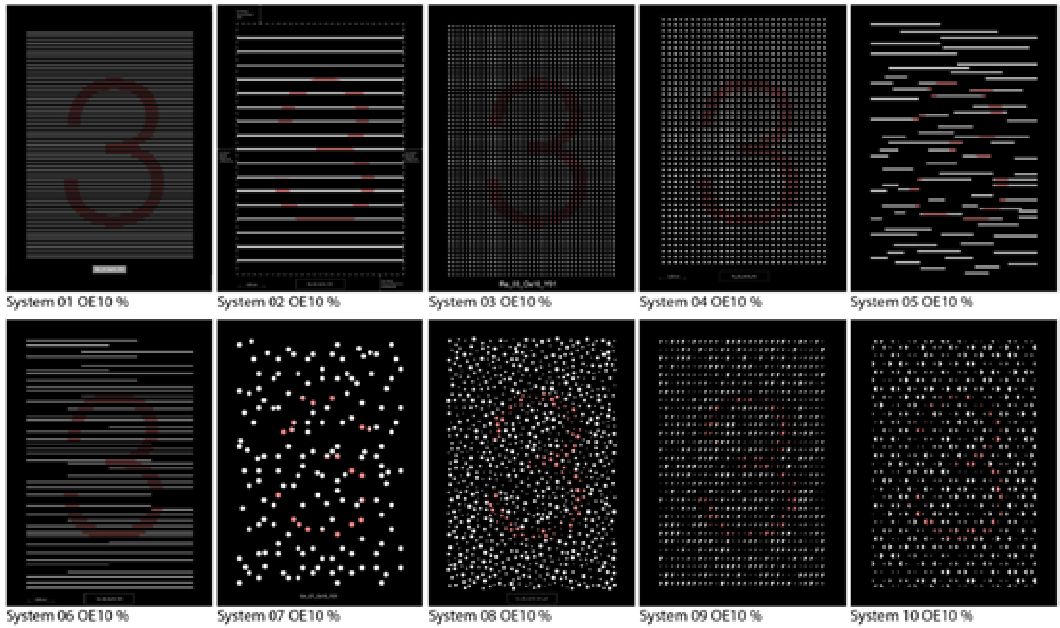

FIG. 18 Influence of Structure on perception. All tables have an opening degree of 10 % - regular structures allow easier recognition of motif underneath the structure

In the space between inner and outer disc, a helical bimetallic spring is located. Such bimetallic springs are also used in thermometer gauges. The bimetal springs in the manipulator allow an auto-responsive control of light and visual transmission as a function of temperature. Currently, the use of electric heating wires is being tested to enable the user to override the auto-responsive reaction of the facade manipulators.

9 RESULTS

9.1 "PERCEPTION & STRUCTURE"

Results from the experimental investigations show that the irregular perforation of facade elements complicates the correct recognition such as the spatial resolution. That fact seems to be different for regular structured elements (Fig. 9). The evolution of the test led to some parameters such as distance, perspective and above all the exposure situation having a great influence on the preliminary results. Consequently, these parameters were largely constricted in the first series of studies to make scientifically viable statements about geometry and degree of opening as influencing factors. After a preliminary examination with 56 test persons between the ages of 21 and 28 years, the first tendencies of the different influencing factors were recognizable.

With an increasing number of test persons, we expect to narrow down the parameters of the membrane that need to be specified. That way, a highly precise and sensitive determination of the perfect membrane facade covering transparent building surfaces will be possible.
On the one hand we are going to study textile membrane facade elements with our experimental setup. On the other hand we will establish test methods to evaluate every structure used in facade construction whose transparency is particular. Technical know-how as well as the cooperation with textile engineers, building technologists, architects and medical specialists for ophthalmology in collaboration with industrial partners provides an ideal basis for innovative working. The continuous

integration of students in the Bachelor's and Master's program of architecture is intended for the future progress of the experiment. Regarding the expansion of the test towards complex structures – such as architectural design – it turns out that already simple structures lead to a high degree of testing complexity.

9.2 RESULTS OF 4D PROTOTYPES

9.2.1 HEX01 – Hexagon Facade (Fabric + SMP)

In the initial laboratory experiments, we observed that the joints did not accurately take their "memory shape" at ambient temperatures slightly above 60 °C. That is why the joints were placed in water baths at elevated temperatures (slightly above 80 °C and slightly above 90 °C). Still, in both cases about 23% of the area remained open. In the further investigations, the joints were overstretched by 10° each. The overstretching caused the surface to close completely. Furthermore, the closing process time is accelerated by a factor of approximately 6 (10.4 sec instead of 60.7 sec). The tests also show that higher temperatures in general accelerate the closing process.

The return of the SMP filaments into their "open state" has proven to be very challenging. In our experiments, it was only possible to move the SMP-Filament from the "open state" (deactivated state) to the "closed state" (activated state). So far, the return of the elements failed due to a lack of feedback force and the hardening of the joints at a temperature reduction to below 60 °C. In the present state of development, SMP filaments without an enhanced feedback force have not proven to be suitable for use in auto-reactive adaptive textile facades.

9.2.2 SOL01 – Bi-metallic Eye (Fabric + Bi-metal)

In the first experiments under laboratory conditions, the surface activation by the thermo-sensitive bimetal strips already worked very well. Currently, tests are carried out under field conditions. In addition, we conduct experiments on the design potential of the activated textile surfaces. It is unclear at this time, which technical textiles can meet both the requirements of the construction practice, as well as the technical system requirements. Nevertheless, the project shows potentials of bimetals for the use of auto-responsive adaptive textile facades.

9.2.3 POL01 – Bi-metal and Polarization

In our experiments, the prototype was heated by an infrared lamp. The temperature difference has not yet been determined, since the actual heating temperature at the bimetallic spring surface could not be measured. It has to be pointed out that the responsiveness of the springs can be manipulated by adjusting the coil and thus customized to the respective location. In the first prototype, a stopper preventing rotation above 90° has not been included yet, but can easily be added.

10 CONCLUSIONS

The technical know-how and cooperation of textile engineers, building technologists, architects and doctors of ophthalmology in cooperation with industrial partners provided very good opportunities for innovative work. The results of the initial studies on perception show that structure geometry, membrane color and reflectance, have a significant impact on the perception of the transparency of membrane facades. In extensive experimental investigations, the research group has already developed more than 80 different conceptual approaches in parallel for system structures of adaptive textile facades. The three conceptual prototypes presented in this work illustrate that, in addition to the specific design of the membrane, the precise selection of the material combination enabling the adaptation process is of particular importance.

It turns out that different material combinations are not equally well-suited for use in textile facades. While bimetals already have been used successfully, so far our attempts to integrate thermo-sensitive shape memory polymers (SMP) in pre-stretched textiles in a reversible motion have failed. The integration of additional auxiliary materials into the textile could potentially compensate for material weaknesses and therefore strengthen their potential.

At this point, it can be concluded that bimetals exhibit superior characteristics with regards to handling as well as material cost among all smart materials under investigation. Furthermore, only with bimetals could a complete return to the initial (deactivated) state be achieved. Therefore, bimetals in particular can be recommended for use as an integral component of 4D adaptive textiles.

So far, research and development was carried out at a conceptual level. Still, the potential of a broad range of concepts for adaptive textile facades became evident in this work. Further development strategies aim at integrating mock-up panels into a large-scale array to be tested under laboratory as well as real-life conditions. The selection of appropriate material combinations tailored to the individual functional principles is crucial for an effective textile facade system. Special attention has to be paid to the durability of the material combination, wherein smart textiles have been widely researched and already reached a sufficient stage of development. The stability of textiles and smart materials in combination, however, has only been tested under laboratory scale conditions and still needs to be verified under real-life conditions.

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Parametric Penrose Tiling – Innovative Exterior Shading Skins

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Abstract

This paper describes the structural & facade engineering process for an innovative flat hospital exterior shading facade built in Mexico City and a double-curved brise soleil skin facade to be built in Ivory Coast for the new Orange Headquarter, both designed by Architects and Artists Elegant Embellishments Berlin (Elegant Embellishments, 2018). Light-weight, curved vacuum-formed-molded elements just t=3mm thin are made of ABS-P6 material (Acrylonitrile Butadiene Styrene - Polycarbonate blend (Campus Plastics, 2018)) and riveted to a hung metal sub-structure, where the entire process from early design to construction is set up parametrically, directly linking connection challenges with form-finding and member sizing. Just two single repeating Penrose tiling (AMS, 2018) elements (the "X" and the "I") are able to create an endlessly climbing visual variety of form, that is also treated with TiO2 surface coating with the designer's aim to reduce NOx/VOC's/SO2 radicals present in polluted cities, activated by ambient daylight and moisture (Land, 2010) (Nakataab et al., 2012)(Hashimoto et al., 2005)(Munusamy et al., 2013)(Schneider et al., 2014) (note: there is dissent about this claim, for example see (Government UK, 2016)).

Keywords

parametric free-form, penrose tiling, ABS-P6 vacuum-formed molding, 3D metal connection design, adaptive metal detailing, NOx-reducing coating

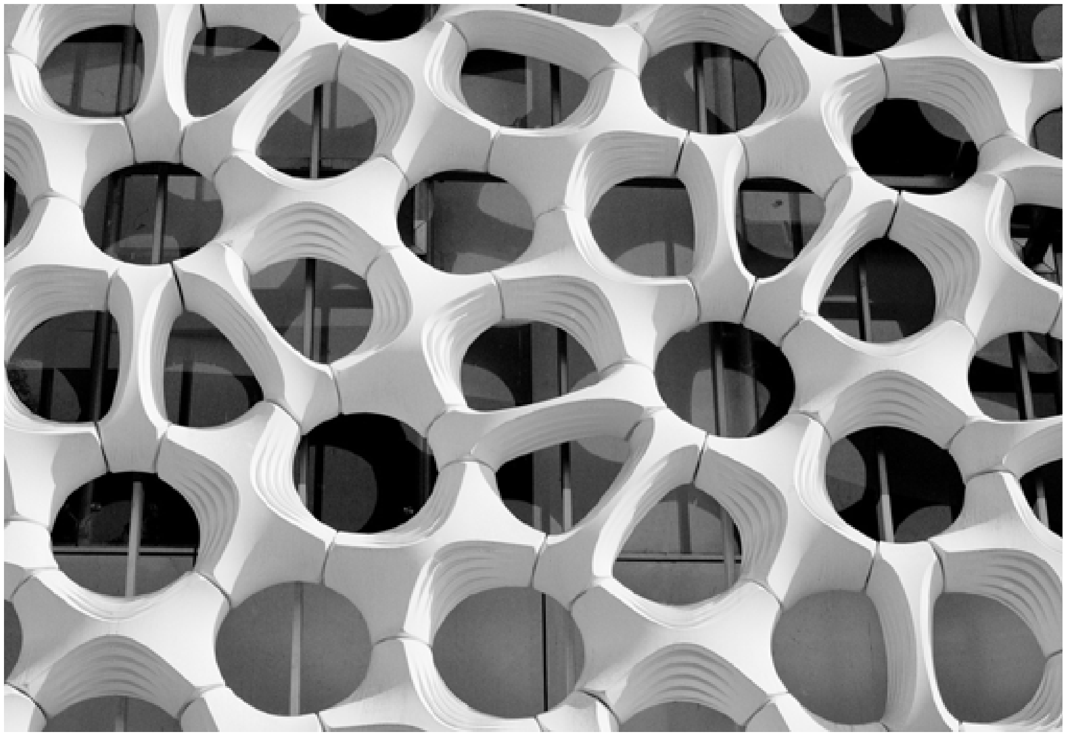

FIG. 1 Basic facade module types "X" & "I", vacuum-formed-molded from ABS/P6 material (Elegant Embellishments)

1 INTRODUCTION

1.1 GENERAL

The search for light-weight building skins using the efficient pre-fabrication approach while offering exterior shading and unique esthetic identity at the same time is presented via two projects that are described in this paper: a ~2500 m^2 hospital over-clad for Mexico City (flat geometry, built in 2012 already) and a ~3500 m^2 brise soleil exterior skin for the new Orange Headquarter in Abidjan (double curved, to be built in 2019).

1.2 PENROSE TILING

Different to recent Architectonical tends of free-form facades that are often composed of hundreds, if not thousands of different panels with unique geometry and associated extra cost, the presented projects achieve their unique "free-form" appearance in a different, more efficient way by referring to five-fold non-periodic penrose tiling patterns that can be originally found in the field of ancient Islamic art and also in chemical crystallography for example. Only two module types evade repeating motifs for economy complexity and scale, the so-called "X" and "I", see Fig. 1.

Penrose tilings (AMS, 2018) are named after mathematician and physicist Sir Roger Penrose, who investigated these sets in the 1970s. In this project approach, rhombus tiling uses a pair of rhombuses with equal sides but different angles. He discovered that a surface can be completely

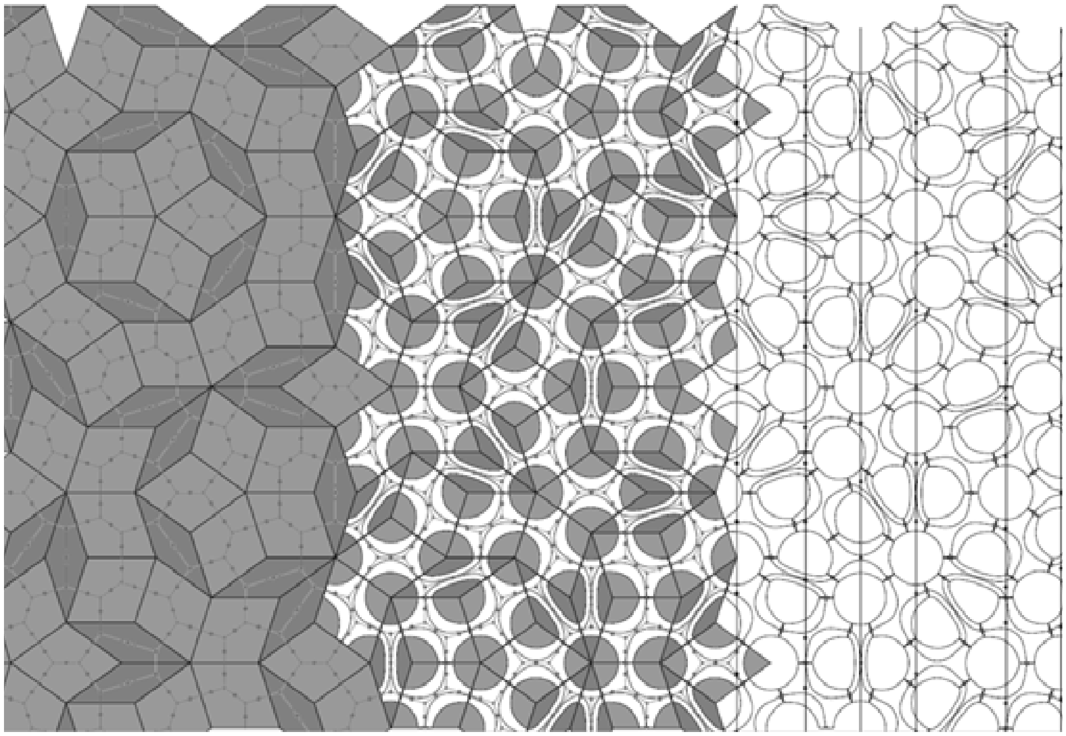

FIG. 2 Generic five-fold Penrose tiling facade set-up, with L-system fractals filled by "X" & "I" elements

tiled in an asymmetrical, non-repeating manner in five-fold symmetry with just two shapes based on the golden rule number Phi = 0.5*(5^0.5) + 0.5 = 1.6180339.. , now known as "Penrose tiles". This is accomplished by creating a set of two symmetrical tiles, each of which is the combination of the two triangles found in the geometry of the pentagon, see Fig. 2.

1.3 VACUUM-FORMED MOLDING ABS/P6

Vacuum-Formed Molding (Protolabs, 2018) is a manufacturing process for producing parts by vacuum-sucking material over a distinctly shaped 3D mold, most commonly thermoplastic and thermosetting polymers. The material for the part is fed into a heated barrel, mixed, and forced into the vacuum cavity where it cools and hardens to the configuration of the cavity.

The self-imposed facade design limitation to use only two distinct elements allows for the cost-efficient approach to vacuum-mold all panels using just two different formwork molds. Since both ductility and strength are required, the material known from automotive ABS/P6 is used for both projects. Acrylonitrile butadiene styrene is a common amorphous thermoplastic polymer, which offers high impact resistance and toughness. ABS/P6 as a Polycarbonate blend offers sufficient ductility needed for post-failure redundancy similar to ductile steel and is suited well for vacuum-formed molding, fabricated in Southern Germany. Its physical properties are given in Tab. 1.

1.4 "POLLUTION-EATING" FACADE

Contaminated air pollution is especially present in Mexico City. Therefore, the exterior skin was chosen to be TiO_2-coated helping hospital patients to get better air quality behind the existing

PHYSICAL MATERIAL PROPERTY TO CODE REFERENCE	VALUE AND DIMENSION
density to ISO 1183	1.15 [g/cm^3]
Young's modulus to 4-point bending EN ISO 178	2200 [MPa]
thermal expansion coefficient to ISO 7991	9.2*10^{-05} [1/K]
water absorption to ISO 62	0.2 [%]
Vicat softening temperature VST B120 to ISO 306	122 [°C]
fabrication shrinkage, estimated during fabrication	0.4 to 0.7 [%]
yield strength to ISO 527	46 [MPa]
strain at yield to ISO 527	5 [%]

TABLE 3 Material ABS/P6 physical properties, determined by t = 4mm thick plate samples (Campus Plastics, 2018)

facade, which led CCN news station to purposely brand the building envelope provocatively as a "pollution-eating facade" (Monks, 2015). The coating has high oxidative potential (active hydroxyl and peroxyl radicals) and the design claims to prevent the plastic cladding from de-grading/dis-coloring.

Coated elements with superfine TiO2-enriched paint with small cascading kinks were created to allow ambient daylight together with humidity to neutralize aggressive NOx particles during pollution-fighting chemical photocatalytic reactions on the element surface (Land, 2010)(Nakataab et al., 2012)(Hashimoto et al., 2005)(Munusamy et al., 2013)(Schneider et al., 2014), claiming to reduce air pollution (such as NOx, CO, SO2, VOC's). The surface kinks also increase structural stability against local plate buckling at the same time.

While this photo-catalyst under UV-light + humidity is claiming to neutralize radicals, its life span is limited to about 5 to 10 years, so the author points out that re-painting of the facade is required to maintain this pollution-eating effect, which puts the effect into perspective due to limited life-span. TiO2 and primers that can adhere to plastic substrate are applied in layers. When the coating wears thin, it can be cleaned with a damp cloth and resprayed without requiring removal of the grid. More systematic quantitative research is required here.

2 METHODOLOGY OF SHAPE

2.1 FLAT SURFACE FACADE – MEXICO CITY/MEXICO

Designed by Elegant Embellishments (elegantembellishments), an over-clad exterior skin was placed over an existing hospital facade, see Fig. 3 and Fig. 4. Due to budget constraints, a vertical mullion grid was hung from the main building facade to pick up the outer panels via local metal extensions that were connected to the inside aluminum sub-structure of groups of "X" and "I" members. The panels themselves were fixed by means of rivets and self-tapping screws to the metal sub-structure.

With a basic material element thickness of less than t = 4mm, molded pieces are easily stackable for transportation. Their light-weight design allows for pre-fabricated units that can be quickly installed on site, see Fig. 5.

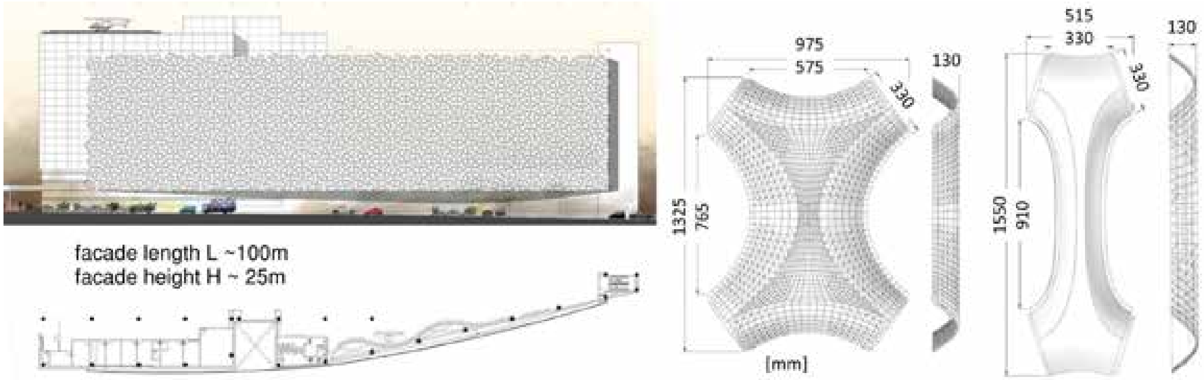

FIG. 3 Torre de Especialidades, Hospital Manuel Gea Gonzales/Mexico City (left, (Elegant Embellishments)), typical X & I panel sizes (right)

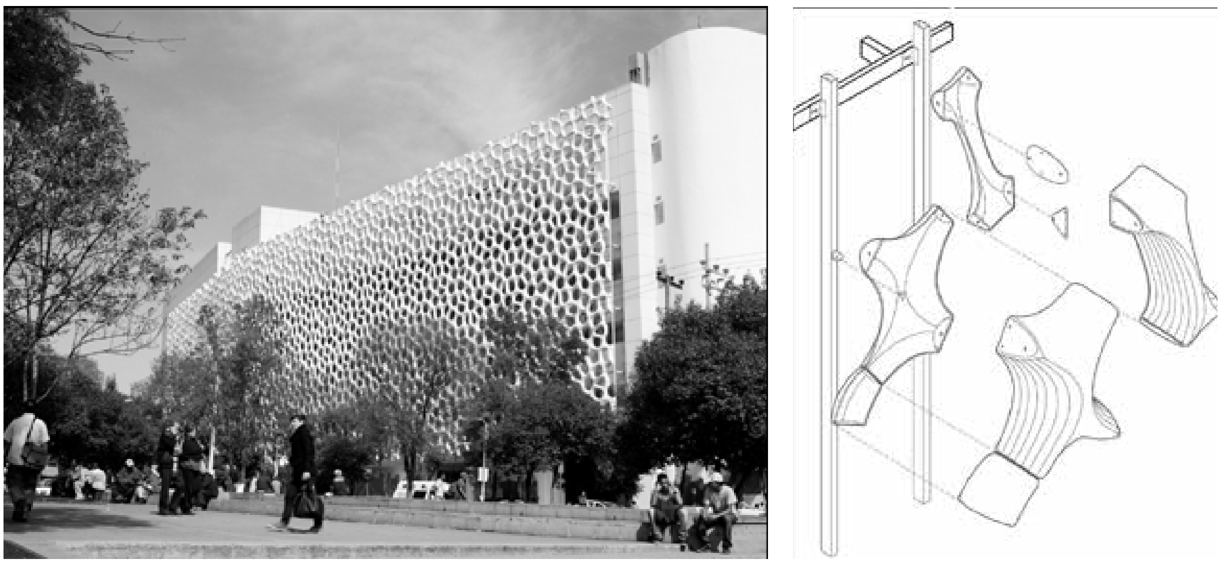

FIG. 4 Built project street view (photo left) – facade geometry is planar and bolted to vertical hangers (isometric right) (Elegant Embellishments, 2018)

FIG. 5 Efficiently stacked basic light-weight elements after vacuum-formed molding in Germany, ready for transportation

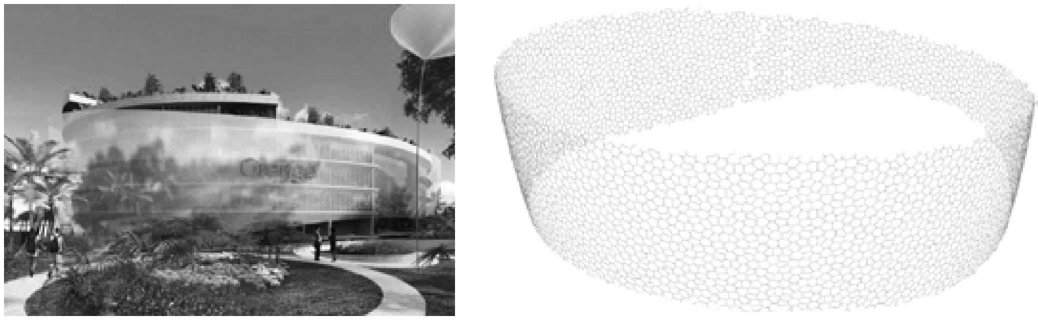

FIG. 6 Circular Orange headquarter building (initial rendering left), chosen penrose tiling brise soleil alternative (right)

2.2 DOUBLE-CURVED FACADE – ABIDJAN/IVORY COAST

A unique, suspended exterior skin was designed by Elegant Embellishments to give the circular Orange Headquarter project a unique architectural identity and at the same time shade office space inside. The early design idea of a more conventional metal mesh was superseded (see Fig. 6). As a second-generation facade approach, this time the aluminum sub-structure is no longer vertical, but follows each member orientation in continuous facets to be fully hidden from the outside.

Furthermore, the open rain-screen system is geometrically no longer a flat surface, but double-curved as a torus instead. Therefore, the five-fold penrose tiling pattern was projected onto the torus surface by means of a method that can be described as "Kangaroo spring relaxation": end points of the pattern are linked to the main building double-curved surface and then step-by-step software runs minimize those distances until convergence is reached.

Kangaroo software (Kangaroo, 2018) is a Live Physics engine for interactive simulation, form-finding, optimization and constraint solving, It consists of a solver library and a set of Grasshopper components, which were linked to CATIA software to map the initially 2D penrose tiling ono the 3D curved torus shape of the outer brise soleil facade of the project. Ten (10x) identical mega-segments are ultimately laid out around the 360° building circular torus footprint, including the main entrance area. The initial master segment can be generated using L-fractals (Lindenmayer system). From the master segment, at its top and bottom sloped edges, some individual "X"- or "I"- elements are subtracted going around the building elevation, leading to the overall inclined continuously sloped facade edges as shown in Fig. 7.

3 STRUCTURAL ENGINEERING RESPONSE

3.1 GLOBAL STRUCTURAL SYSTEMS

For both projects, it was chosen to hang the exterior facades off from horizontal outriggers at the top, to avoid permanent compression in the substructure, see Fig. 8. While the Mexico system has vertical hangers that are still visible through the facade pattern openings, 2nd generation Abidjan will hide all aluminum mullions (alloy AW 6061–T66) behind the opaque pattern areas, hence "faceting" behind the penrose pattern. Sloped wind props hinged at both ends transfer facade wind loading back to the main building slab edges.

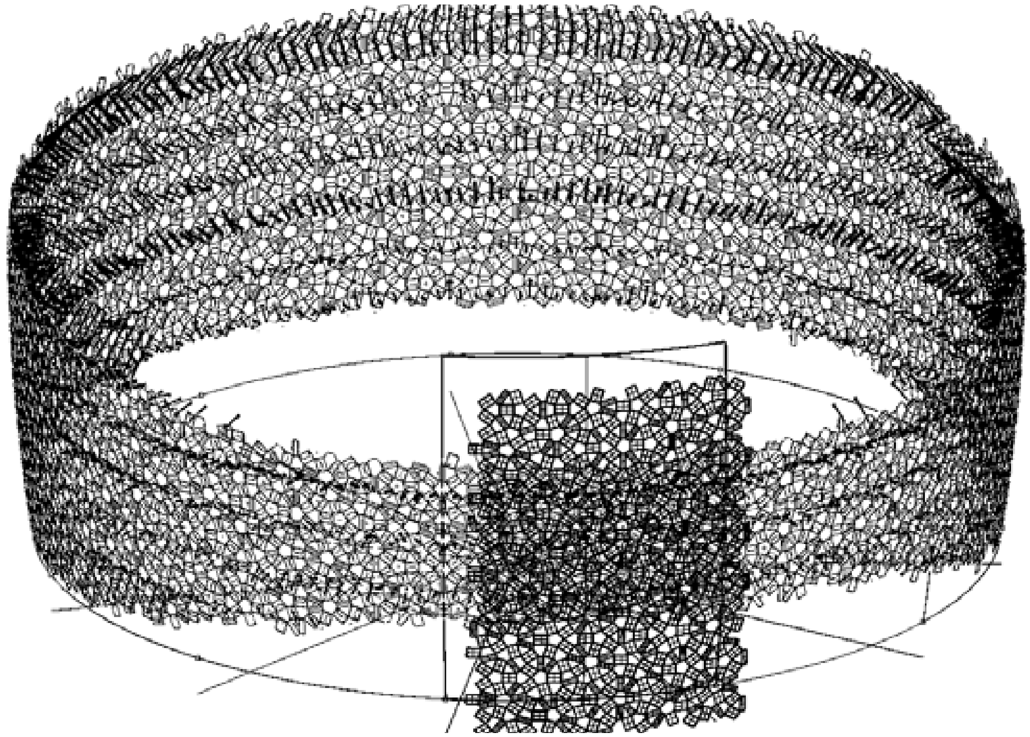

FIG. 7 Overview of double-curved surface generation – 10x basic mega-modules are seamlessly projected over the torus (credit: Frank Melendez, City College NYC)

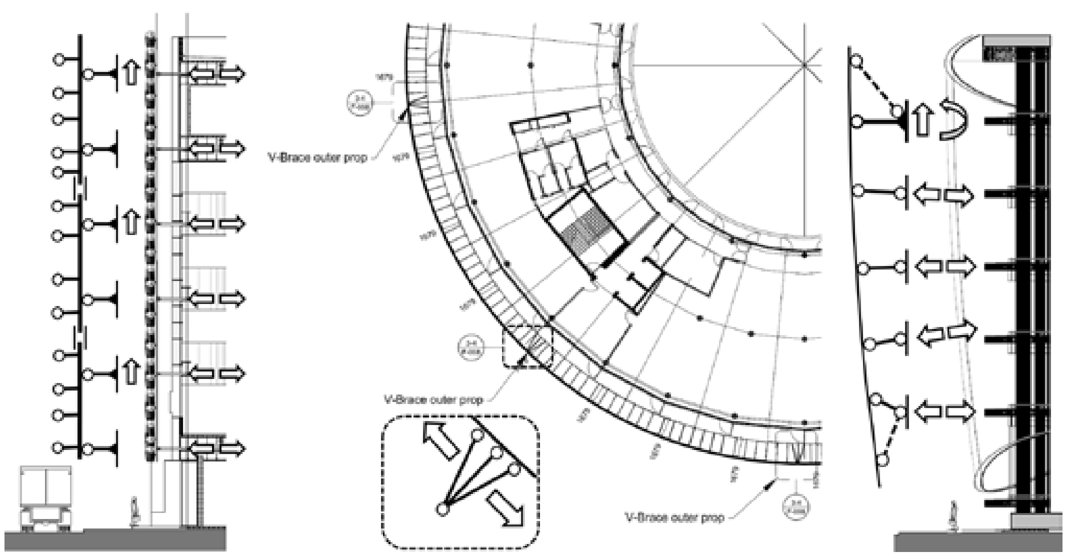

FIG. 8 Schematic structural sections for dead load & wind, Mexico (left), Abidjan horiz. (center) and vert. section (right)

The Mexico facade tracks are close to the main building slab edges and framing action can provide sufficient lateral stiffness to resist seismic loading and winds acting parallel to the facade line. For Abidjan, the bris soleil sits further outbound of the main building slab edges, with a cavity approx. 1.5 to 2.0m wide. Due to the sloped nature of wind props, each of the 10x master modules gets a diagonal bracing, to resist wind forces that might otherwise rotate the entire exterior skin around the building central axis.

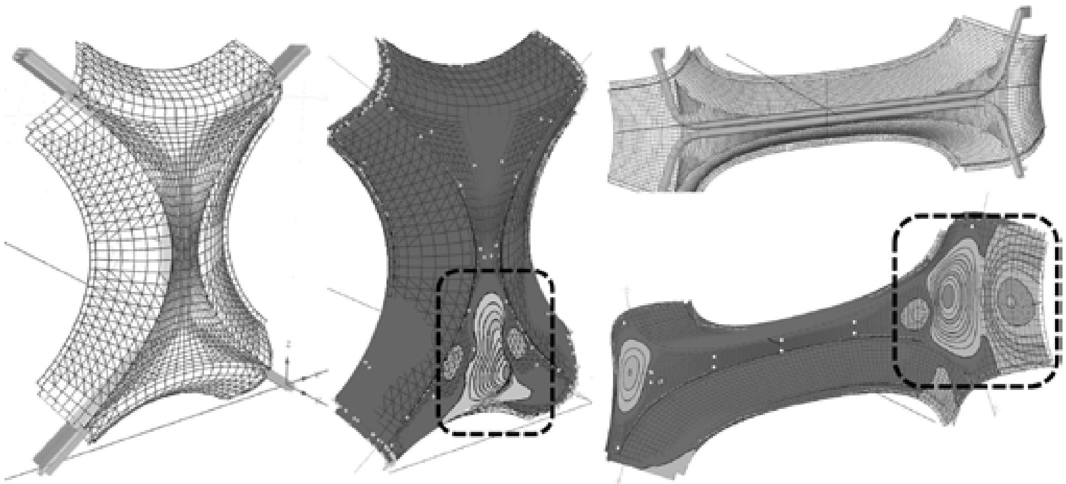

FIG. 9 Figure 9: „X" & „I" module FEM lowest eigenmodes under dead & wind loading (LaufsED, 2018) – local plate buckling safety >5.0 – ok

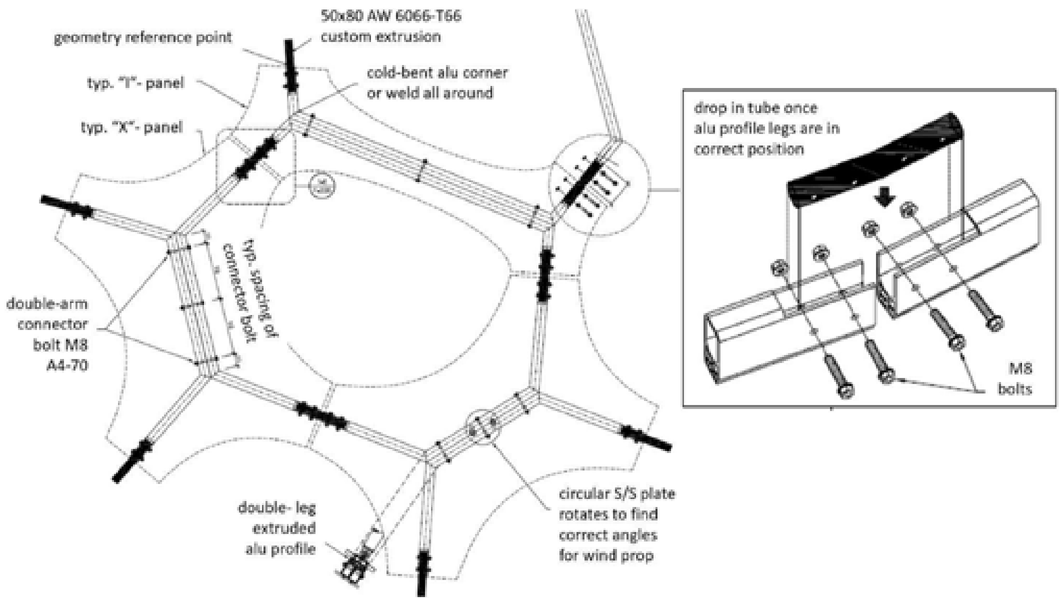

FIG. 10 Module alu sub-structure, visually hidden behind opaque panel areas; Abidjan facade sub-structure approach

3.2 LOCAL MODULES & STRUCTURAL CONNECTIONS

The two main modules were shaped in a three-dimensional way to have suitable structural depth to keep deflections under wind loading small (<L/200, with L longer panel dimension). Stainless steel rivets & self-tapping screws were specified that link the ABS/P6 base material to its metal sub-structure. 1:1 connection testing was carried out to verify tension and shear capacity of the assembly with a global safety of >3.0. Reaction forces were determined via a 3D combined shell and beam model as usual.

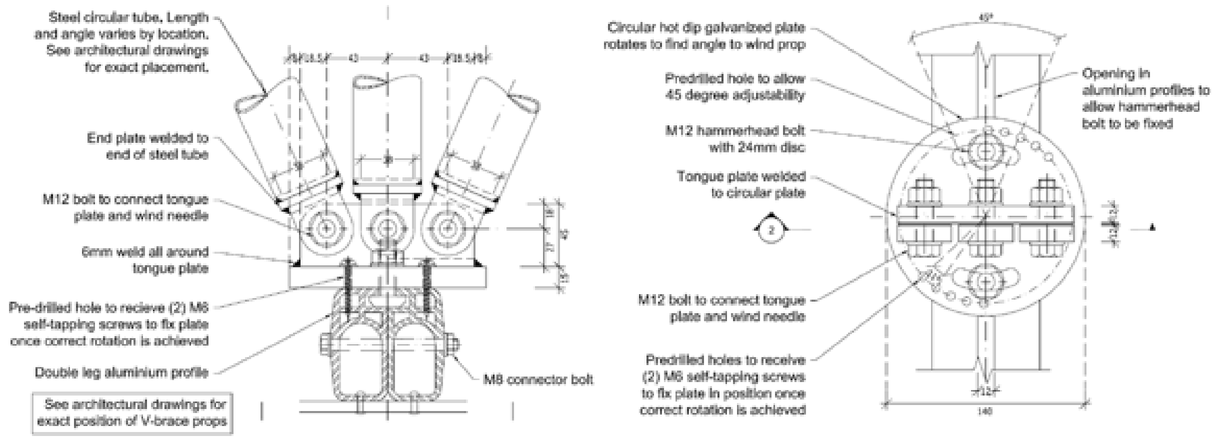

FIG. 11 Example of flexible Abidjan connector design to take random angles in space (Protolabs, 2018)

Local structural stability of the modules was verified using the stability eigenvalue method, with panels modeled via 3D iso-parametric shell elements. As examples, some relevant eigenmodes are shown in Fig. 9, being local plate buckling shapes, depending on wind direction and load combination. Global safety of >5.0 against elastic material bending stress capacity is achieved. Local connection reaction forces were compared against testing values (pull-out, shear and interaction), with a global safety of > 3.0.

For Abidjan, inclined mullions meet in space at slight angles due to the torus curvature, see Fig. 10. To solve various situations with just one detail that can be handled on site also, a circular inlay tube was developed, which can be bolted to both aluminum extrusion ends. Extrusions therefore allow for circular inserts to fit, also at their inner surface facing the main building they have a local extension to receive hammerhead screws which form the connection over to all wind prop ends. They can be freely "sliding along" the mullions prior to locking them up, allowing to overcome small tolerances in prop length and install inaccuracies, see Fig. 11. Note how one single alu extrusion cross section is able to handle the free-form geometry, receiving rivets and hammerhead bolts as needed. Extrusions double-up at the center of each module, from which then individual branches spread out to the adjacent modules.

4 INSTALLATION

The Mexico facade was installed from the outside of the building via mobile crane, see Fig. 12. First, outrigger cantilevers with welded-on end plates were connected to the main building structure slab edges; on their outer ends, horizontal RHS tracks were welded-on to the cantilever tips running along the straight facade lines, with splice joints every few bays to allow for lateral thermal movement. Vertical mullions (RHS 50 * 100mm) were then connected to the rails (approx. spacing @1000 to 1500mm o.c.) via L-clips with slot holes for tolerance adjustment. Vertical hangers are also spliced every few floors to allow for vertical thermal movement.

Up to 8 base "X" & "I"-elements were pre-assembled on the ground (bolt together end plates with stainless steel/neoprene rivets) and then lifted up into place, where the pentagon brackets were rotated into place and then connected to the vertical hangers via hollo bolts. Given the non-repetitiveness of the penrose tiling pattern, receiving tricon stainless steel plate positions on the module backside have to be worked out in elevation prior to install and modules need to be numbered, which is a still reasonable logistic effort that can be managed fine.

FIG. 12 Module segments during installation, bolted to painted metal sub-framing (Elegant Embellishments, 2018)

The Abidjan facade will be installed via a ground floor mega rig that can help create each mega module, where some on-site aluminum mullion bending is foreseen to make all ends perfectly fit to receive the circular adapter link pieces (see Fig. 10, 11). Temporary lifting clamps will be fixed within the alu slots via hammerhead bolts and then crane-lifted up into place. Metal embeds into concrete building slabs will anchor main moment cantilevers and hinged wind prop ends. Installation is set to take place in 2019.

5 SUMMARY

The presented facade projects above show how the interaction of form, material and digital geometry programming produces innovative engineering results that are verified to code and use small-scale fastener testing as usual. Early-on 3D design in conjunction with vacuum-formed molding of only two unique pieces allows to control quality and appearance, including up-front consideration of tolerances and erection sequencing on site.

While a classic structural engineering understanding of force flow, system set-up and connection verification is still required, modern facade innovation however requires full integration of 3D geometry programming as well as an openness to explore new materials (here: ABS-P6) and embracing the creative initial design idea (here: Penrose tiling adapted via CATIA software as brise soleil rain-screen system). In the overlap of different disciplines one can find innovation. In other words: a structural engineering education without solid skills in controlling 3D geometries via suitable software and an outreach to chemistry and material science knowledge with regards to material opportunities and coatings falls short to produce progress in the field.

In 2012, the facade was installed at Torre de Especialidades, Hospital Manuel Gea Gonzales, Mexico City. According to the Architect, it is meant to reduce daily air pollution and achieve a new unique hospital appearance at the same time. Ivory Coast Abidjan Orange Headquarters two-way curved facade prototypes mock-up is set for fall 2018, with installation on site scheduled for 2019, to be the first of its kind on the Globe.

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Market survey of timber prefabricated envelopes for new and existing buildings

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Abstract

The building sector has revealed a need for process optimization, mirrored by the ongoing discussion around industry 4.0 and increasing automation in building design and construction. Within this context, the prefabrication and standardization of building elements provide interesting opportunities for optimizing the construction process. Off-site fabrication of building envelope and systems can provide significant advantages in terms of process, quality and safety management. This paper presents an outline of state-of-the-art building opaque envelope prefabrication, with particular focus on timber building skins, through a collection of best practices both in the field of building retrofit and new construction. This research is the result of shared research interests and synergies among the Institute for Renewable Energy at Eurac Research and the Innovation in Applied Design (IAD) Lab at the University of Sydney. Results highlight current limitations of envelope prefabrication and outline development opportunities both at technical and production process level. These findings and the conclusions we draw from them will set the foundations for expanding the adoption of an industrialized fabrication approach in the construction environment.

Keywords

Envelope prefabrication, off-site manufacturing, envelope retrofit, timber construction, construction process

1 INTRODUCTION

In recent decades, the construction sector has been evolving with the aim of achieving increased sustainability objectives. This has been pursued through the adoption of life cycle design methods, as well as application of industrial production principles and advanced manufacturing concepts (Aitchison 2018). In practice, research and technology development activities are translating these objectives into a so called "lean" production approach, which is generally acknowledged as the combination of sustainability in resource management (human and physical) and productivity optimization.

The sustainable use of resources in the building sector can be implemented through: use of certified environmentally friendly materials, design of energy efficient construction solutions, or even the adoption of a circular economy design approach. The latter is based on the re-use of building elements at the end of service life to minimize environmental impact and optimize the building economic cycle (Tebbatt Adams, et al. 2017). Productivity in the building sector is low if compared to other manufacturing branches and the average global economy (McKinsey Global Institute 2017). The authors propose prefabrication as a means to pursue both sustainability and productivity in a synergic manner, which is able to boost construction productivity through the following: (i) coordinated work of several players along the value chain; (ii) enhanced execution speed and quality; (iii) advanced technological design effort and (iv) investment optimization, with a focus on process innovation. Off-site fabrication of building elements (or prefabrication) allows for a deliberate shift of works towards the manufacturing site rather than the traditional construction site, according to the degree of industrialization that is foreseen for a specific real estate development or renewal operation (Smith 2010). The adoption of this approach can increase productivity up to 50-60% (McKinsey Global Institute 2017). However, it is important to point out that it is not enough to move building production from the building site to the factory, rather, it is also important that the manufacturing mindset be adopted to harness the full value proposition of prefabrication.

The market survey presented in the following section is focussed on the prefabrication of timber building envelopes. This scope is viewed as a crucial research priority given the high tempo at which structures and systems are already able to be built and produced.

1.1 AIM AND SCOPE

This work is the result of research synergies among the Institute for Renewable Energy at Eurac Research and the Innovation in Applied Design (IAD) Lab at the University of Sydney, whose activities focus respectively on designing energy efficient envelopes for building retrofit on the side of Eurac, and advanced prefabrication methods for high rise timber buildings on the side of the IAD Lab. In particular, this paper focusses on prefabricated envelopes conceived on a timber-based structure (the core expertise of both institutions). The use of timber responds well to both the sustainability and productivity challenge in the construction sector. Indeed, wood is a carbon neutral and renewable resource, in line with the current de-carbonization objectives set by the European Commission (European Parliament 2010), as well as highly compatible for prefabrication and industrialized production. In addition, it is lightweight and characterized by high thermal performance, features that make it even more suitable for use in the building envelope.

The aim of this research is to advance knowledge in the field of envelope prefabrication and construction process optimization both for existing and new buildings. This is done through a technical solution market survey to outline main achievements, limitations and perspective research and technology development in the field.

2 TAXONOMY OF BUILDING ENVELOPE PREFABRICATION

Envelope elements prefabrication dates back to the 1950s and is generally associated with the post-World War II need for rapid housing supply to the population. In the latest years, the concept has been refined to describe the production and manufacturing of construction elements off-site to the highest possible degree, so to minimize works to be performed on-site, apart from mere assembly operations (Smith 2010). The 1990s saw a rather systematic push of industrial production concepts into the building sector, such as mass customization or lean manufacturing. However, these concepts are having a hard life within the construction market, struggling to be truly integrated in the value chain of building production that persists in being rooted on an analogue based approach (McKinsey Global Institute 2017).

It is commonly agreed that the attempt to drive the development of the construction sector towards an industrialized approach to building production is based on the huge perceived advantages of off-site working, such as: increased productivity in terms of time and cost, increased workers safety, enhanced quality of the output, together with a more sustainable use of resources in terms of construction site logistics, components manufacturing and waste minimization. Prefabrication is based on three core promises: quality, cost and timeliness. These challenges have been a recurring idea in housing and construction since the last two centuries, still without being totally fulfilled in terms of objectives. More recently, the concept of prefabrication has been enriched with environmental sustainability and possibility to integrate personalized features (Aitchison 2018). Among those, multifunctional envelopes include a set of possibilities to integrate system elements, allowing for enhanced energy performance of the building (Babich, et al. 2018).

As demonstrated by the successful example of unitized glazed curtain walls in tall construction, the use of standardized components within the envelope of a building allows for a quick, reliable and safe installation phase, shifting product's detailed engineering work to the manufacturing site (protected environment) and significantly reducing the need to work at height. Despite the widespread use of unitised facade elements in high-rises, the mid to low-rise building sector is characterised instead by the use of traditionally-conceived multi-layer opaque envelopes, which allow for excellent energy performance but still rely on the traditional ad-hoc and site-assembled approach to fit the case-specific features. This lack of uptake implies a consistent rise in production costs, due to the impossibility to access an economy of scale.

3 METHODOLOGY

The authors analysed a set of case studies acknowledged as best practices examples by the technical and scientific community, both in the field of new construction and retrofit operations. Cases are presented in brief to allow the reader a general understanding of system technical features, then compared along the reveal construction management dimensions, such as (i) use of fixed scaffoldings; (ii) level of prefabrication, according to the need to perform additional work on the prefabricated wall unit after its installation in place; (iii) technical/economic convenience with respect to traditional, single components based, construction techniques. In the case of new buildings, the technical/economic convenience parameter has been discarded from the analysis, in light of the significant market differences connected with the geographic locations of the presented buildings (Europe vs. Canada, as seen in 3.2).

FIG. 1 TES EnergyFacade project – process digitization (source: Gumpp & Maier)

FIG. 2 TES EnergyFacade project – panel installation (source: Gumpp & Maier)

3.1 RETROFIT CASE STUDIES

Europe's existing building stock is much older, on average, than that of Australia and even the USA. Despite construction traditions that date back many centuries, most of the existing buildings are affected by severe underperformance from an energy and comfort point of view. A number of collaborative research projects in the last decade have concentrated their design effort in the field of existing buildings retrofit with advanced technological systems that can integrate renewable energy sources (RES) and actively contribute to European decarbonization objectives. In this section, the authors present a collection of projects in the field of envelope retrofitting using prefabricated elements, characterized by high technology readiness level and real demo-case sites, followed by a comparison of the most significant prefabrication related criteria (see Tab. 1).

TES Energy facade project (http://www.holz.ar.tum.de/forschung/tesenergyfacade/) developed an off-site fabricated modular facade to be applied in residential building retrofit (Larsen, et al. 2011) (Fig. 1 and 2). The approach has been successfully developed and released in two versions, TES (2009) and smartTES (2013), the latter also integrating system components in facade modules. The project is based on a systemized digital workflow that embraces the whole value chain from measurement, to planning, fabrication and mounting. The main technical features can be summarized as follows: (i) large panel size, to cover one storey of the building; (ii) timber framed insulated cassettes; (iii) external cladding, sills and reveals as well as steel weather profiles; (iv) integrated windows.

FIG. 3 iNSPIRe facade installation sample, external side view (source: Gumpp & Maier)

FIG. 4 iNSPIRe facade installation sample, internal side view (source: Gumpp & Maier)

iNSPiRe – Systemic Energy Renovation of Buildings (http://inspirefp7.eu/) developed an off-site fabricated modular system for efficient energy renovation of residential buildings, with the aim of minimizing construction works on site for the deep renovation of facade, roof and energy systems (Fig. 3 and 4). This project has further developed the results achieved in the TES Energy facade project, focusing on system integration. The designed facade has been successfully deployed in two different case studies. The main technical features can be summarized as follows: (i) large panel size, to cover one storey of the building; (ii) timber framed insulated cassettes; (iii) external cladding, sills and reveals as well as steel weather profiles; (iv) integrated windows. The iNSPIRe facade also integrated multifunctional system components, such as micro heat pumps, heat recovery units and related ducts (Dermentzis, et al. 2014) (Ochs, et al. 2015). Some hydraulic and aeraulic components have been integrated in a dedicated system shaft, prefabricated as well and integrated within the facade allowing to bridge the building apartments at different floors.

FIG. 5 4RinEU facade design process (source: Boligbygg Oslo FK)

FIG. 6 4RinEu facade installation sample, external side view (source: Municipality of Oslo)

4RinEu – Reliable models for deep renovation (http://4rineu.eu//) makes a step further with the aim of supporting the use of off-site fabricated renovation packages with design methodologies and reliable business models (Babich, et al. 2018) (Fig. 5 and 6). As for the case of TES EnergyFacade and iNSPire, this facade is equipped with the same layers and components before leaving the construction site. However, the construction site shown in the pictures below has benefitted from process optimization not only during the manufacturing phase, but also for construction site management. In fact, the production facility is located in a short distance (3-4 hours) from the site and modules were delivered just-in-time for installation.

FIG. 7 SINFONIA project – panel installation (source: Benedikter Architekten)

FIG. 8 SINFONIA project – panel production (source: Benedikter Architekten)

FP7 SINFONIA project - Low Carbon Cities for Better Living (www.sinfonia-smartcities.eu), has worked on the development of an extensive set of energy saving measures spanning from smart transportation systems to envelope retrofit solutions (Fig. 7 and 8). In this frame, prefabricated module types have been chosen by the design team as facade concept, designed and applied in several construction sites in Bolzano (Italy). Authors believe that there is potential for replicating this approach in future works – even if some conceptual design work still needs to be performed to eliminate the need for onsite work completion. Main technical features that characterize this solution can be summarized as follows: (i) TJI timber frame structure, with massive studs applied as external frame and double T shaped composite timber elements applied as intermediate reinforcement, to confine soft insulation material; (ii) regulating layer, made of compressible insulation material applied at the back of the prefabricated module and covered with waterproofing layer - this work is performed offsite and allows to speed up the installation process; (iii) connection system to the existing slabs based exclusively on T shaped metal plates; air and water tightness fixing applied manually between the panels after their installation; (iv) external cladding installed on-site, as in traditional construction.

3.2 NEW CONSTRUCTION CASE STUDIES

Prefabrication of the envelope for timber construction has seen an increased interest in the last two decades, as it allows for quickly covering of the indoor volume and so protecting timber elements from weather agents since the very first days on the construction site (Gasparri, et al. 2015). In addition, the rise in average building height has created market need for envelope solutions that can be installed in a short time and guarantee high workers´ safety level. This paragraph presents a short collection of best practice examples in the field, proposing a simple comparative analysis of the most significant prefabrication related parameters (see Tab.2). Differently from the retrofit case study collection, economic parameters are not included, as the geographic marketplaces in which the buildings are standing are not directly comparable.

Holz8 building in Germany (2011) is a residential building composed of massive timber components, with preassembled external walls. The prefabricated components are made of the following: (i) CLT load bearing structure; (ii) insulation; (iii) windows and shutters. The facade system is highly prefabricated, but joints between wall units require manual completion from the outside with the use of scaffolds.

CASE STUDY ID	FIXED SCAFFOLDING	PREFABRICATION LEVEL	TECHNICAL/ECONOMIC CONVENIENCE
TES EnergyFacade	Yes – lifting crane + scaffolding	High – all layers included	Average cost, the cost is above average when active system components are integrated
iNSPiRe	Yes – lifting crane + scaffolding	High – all layers included	Cost above average, due to integration of active system components[1]
4RinEU	No – lifting crane + mobile construction platform[2]	High – all layers included	Average cost, the cost is above average when active system components are integrated
SINFONIA	Yes – lifting crane + scaffolding	Medium – external cladding is installed onsite	Average cost, room for improvement in the production process

1 In this case, higher costs are partly justified by the fact that this project brought to market a facade technology that was still a prototype until it was developed within the project frame

2 The construction site is a two storey building, so the lack of scaffold is also facilitated by the specific site features

TABLE 1 Retrofit case studies comparison according to relevant prefabrication criteria. The technical/economic convenience is evaluated through a benchmark to an average price for advanced facade systems, fixed at approximately 2x the price of a traditional external insulation with ETICS.

FIG. 9 Facade installation process for the Holz8 building in Bad Aibling (source: www.huber-sohn.de)

FIG. 10 Installation of LCT ONE facade system through scaffolds (source: ww.creebyrhomberg.com ©Darko-Todorovic|Photography|adrok.net)

LifeCycle Tower One in Austria (2012) has been designed with the aim of reaching Passivhaus standards despite guaranteeing reduced construction time through prefabrication. The prefabricated wall components are made of the following: (i) timber frame support, free from any load bearing function; (ii) insulation and watertight layers; (iii) external cladding; (iv) windows. The facade system has a medium degree of prefabrication, as the watertight layer and the cladding were applied on site through the use of scaffolds.

Ywood «L'Ensoleillée II» building in France (2013) has been developed with the aim of providing clients with flexible solutions characterized by reduced construction time and cost. The prefabricated wall components are made of the following: (i) CLT load bearing structure; (ii) insulation; (iii) external cladding and (iv) windows. This facade system is highly prefabricated, even if vertical joints are completed on the construction site, acting from mobile platforms. A limited use of scaffolds was needed to complete building corners.

Brock Commons building in Canada (2017) has been designed with the aim of constructing the whole envelope without the use of scaffolds. This case study is not a timber-based technology, even if the design phase has seen the use of timber as a possible option. However, it is interesting to include the

FIG. 11 Facade installation process for the Nexity Ywood «L'Ensoleillée II» building in Aix-en-Provence (source: © Nexity, Yann Bouvier)

FIG. 12 Brock Commons fully prefabricated envelope installation phase (source: www.naturallywood.com)

case in the review as it presents interesting elements in perspective for timber-based application as well. This facade is made of steel stud wall elements, which are hanged onto concrete floors through adjustable connectors as in curtain wall facade. This facade system has a high degree of prefabrication, as the panels were delivered with all layers to the construction site. However, if on the one hand, works on the envelope have actually been completed without any need to act from the outside of the building, the lack of scaffolding led to a bitumen based manual sealing operated from the inside, which seems to be "unaligned" with such a high degree of prefabrication.

4 RESULTS DISCUSSION AND CONCLUSIONS

For the presented case study buildings in section 3.1, the average cost for square meter of renovated facade is in the range of 400-900€. Of course, local construction market differences need to be taken into account, as we estimated that they may affect the total cost of works up to 20%. However, a simple comparison with the result of the IEA ECBCS Annex 50: Prefab Systems for Low Energy/ High Comfort Building Renewal research back in 2010 concluded a renovation cost equal to approx. 1000 €/m^2 of facade (International Energy Agency 2012), and highlights that the increasing interest and design effort in the direction of prefabricated systems for facade renovation are working in favour of cost reduction.

Current limitations to the adoption of prefabricated facade systems for building retrofitting at a larger scale are mainly ascribed to the higher cost with respect to non-prefabricated renovation systems, due to:

- Longer lead-time, with the necessity for more coordinated R&D before projects even begin to establish the capacity to deliver new products on time and at a guaranteed cost.
- More intense design effort with respect to traditional construction sites, due to the difficulty in adapting a high degree of prefabrication to the variability of geometry in existing buildings (i.e. construction tolerances).
- Lack of appropriate production infrastructures for the assembly of prefabricated panels. This reduces production speed, increasing costs, and capital expenditure required to procure such a capacity.
- Use of more advanced technological solutions with respect to traditional energy performance renovations, such as: integration of renewable energy sources (e.g. photovoltaic modules, solar thermal collectors); integration of HVAC systems. These components are costly with respect to a passive envelope solution, but the added value to the building in terms of comfort and performance deserves consideration (Jakob 2006).

In the case of envelope prefabrication for the timber high-rises, as seen in section 3.2, the state-of-the-art analysis shows how the design efforts carried out so far have not managed to solve the "prefabricated joint dilemma" yet. In fact, despite varying levels of facade panel prefabrication spanning from medium to high, which means including all functional layers and required components to ensure envelope correct function, junctions still require manual work to be performed

CASE STUDY ID	HEIGHT	FIXED SCAFFOLDING	PREFABRICATION LEVEL
HOLZ 8	8 storeys	Yes – lifting crane + scaf-folding	*** cladding and windows installed offsite, interfaces completed onsite
LCT ONE	8 storeys	Yes – lifting crane + scaf-folding	** windows installed off-site, cladding and interfaces completed on site
YWOOD BUSINESS	3 storeys	Yes – lifting crane + platform + corner scaffolding	*** cladding and windows installed offsite, interfaces completed onsite
BROCK COMMONS	18 storeys	No – lifting crane only	*** fully offsite finished panels installed onsite

TABLE 2 New construction case studies comparison. Prefabrication level is rated 1, 2 or 3 stars (*), for lower to higher prefabrication degree.

on-site in order to guarantee air and water tightness. The root cause of these unsolved issues can be ascribed to the variety and complexity of multi-layer envelope systems, particularly in terms of number of parts and their reciprocal interrelation. In particular, main criticalities are:

— The gap along the production value chain in terms of design methods, such as Design for Manufacturing and Assembly (DfMA). To date, the manufacturing of opaque multi-layer envelope systems requires a much higher number of assembly operations when compared to unitized glass facades.
— The lack of coordination among suppliers to integrate different construction methods, optimise the use of materials and connection systems (e.g. screws, nails, rivets, glue) and develop new organic solutions in accordance with specific product requirements.

Further research effort in the future will focus on highlighting the extra-costs related to prefabrication, both in terms of design and construction, to determine which steps of the value chain are more likely to produce savings in the overall process. In addition, a point should be made on quantifying the productivity increases that can be targeted through the adoption of automated production lines.With respect to new construction, further research steps will also include the design of construction site-ready solutions, which allow for complete installation without the need of manual intervention after panel mounting.

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Parametric Poetry-Integrated Solutions for Complex Geometries with Structure and Skin

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Abstract

This paper describes our integrated parallel approach to optimizing structures, using generative computational modelling systems, working alongside our clients, structural engineers and construction companies. Nowadays, there is a move towards integrated design systems in contemporary design. Here we describe our design for a pavilion, where structural elements were optimized not only in terms of their structural stability, but also production, thereby reducing costs. This integrated approach allowed us to simultaneously examine, on one hand, the architectural impact of the structural elements and the associated covering membrane, and on the other, its structural stability and the extent of material required. The process led us to set up a parametric system to study the pavilion's architectural geometry. A similar system then analysed its structural integrity, and another, the production costs. The resulting system of components form an interrelated whole, where each has a direct impact on the other. To test out various pavilion geometries, we undertook an iterative mathematical analysis, based on the logic of evolutionary calculations in three dimensions. Following that, several potential pavilion forms were examined and weighted according to various factors: architectural, structural, material and financial. The resulting structure – a system of wooden ribs combined with an outer membrane – was then further tweaked to optimize it as an integrated structural system. Compared to a traditional design approach, which is more or less consecutive and creates a loop, the advantage of this process is that the constitutive elements are always considered in parallel. This speeds up the design and analysis process, and is an efficient method to determine the final production cost. In the case of the pavilion, this meant we were free to experiment with various designs, while always keeping costs in mind. We were, for instance, surprised to discover that through optimizing the integrated rib and membrane structural system, the dimensions of the structural elements turned out to be far smaller than we had originally envisaged. All this affects the production schedule, the material flow and ultimately, the final cost of the pavilion.

Keywords

Computational Design, Integrated design systems, Optimization, Parametric modeling, Complex geometries, Wooden construction, Membrane systems, Evolutionary optimization.

FIG. 1 The Multihalle in Mannheim, Germany (Carlfried Mutschler with Frei Otto)

FIG. 2 Autobahn Chapel Siegerland, Germany 2009-2013 (schneider+schumacher)

1 INTRODUCTION

Humans have come a long way since they inhabited natural shelters, as exemplified by the complexity of architecture today. In prehistoric times, humans fulfilled their need for shelter by finding a naturally appropriate location, like a cave or an overhanging cliff. Later, hunter-gatherers began to live a nomadic life and to create settlements that led to the appearance of the first constructed shelters. One might argue that this episode marked the birth of the tent – a temporary shelter, assembled within a short time span and later dismantled and carried to the next location. This portability became necessary due to the nomadic nature of society and Bedouins in Arab countries epitomise this form of lifestyle, and still practice it today. The tent represents the most rudimentary form of portable architecture, and it is based entirely on two primary attributes – a structural frame, and a skin. This concept has remained constant in the entire genealogy of the tent throughout the passage of time. The construction principle of a modern tent hardly differs from that of a primitive tent.

The tent-like works of Frei Otto in the latter part of the 20th century show an unrelenting desire to further the boundaries of using structure and skin in a single integrated system. The Multihalle Hall in Mannheim, Germany, designed by Carlfried Mutschler together with Frei Otto (1975) (Fig.1), offers one of the best examples to demonstrate how this principle can be stretched to the limit, in terms of form and structure. The design system is based on a wooden rib structure covered by a membrane skin. The most fascinating aspect of this system is the form-finding principle that is embedded in it. This wooden structure was dictated by the parameter of the membrane and wooden elements acting as a single structural entity once the elements are brought into position. The final form of the roof thus derives from an organic form-finding process that is influenced by a combination of structural forces and the desired spatial quality.

The new pavilion designed by schneider+schumacher for the Frankfurt Book Fair (Frankfurter Buchmesse) embodies similar principles, and takes them to the next level, employing the computational tools available today. These allow one to combine the process of form-finding with form definition, and to thereby create an integrated design process. The factors governing the geometry are also those that will ultimately influence the final cost of the project, so an unprecedented level of optimization can be achieved in this integrated process. By analysing the hybrid configuration of structure and skin as a single entity, it is now possible to test how the independent elements influence one another and thereby to optimize each one of these elements, creating an integrated system.

2 INTEGRATED DESIGN – FORM, STRUCTURE, MATERIAL AND COSTS

The client's brief for the Book Fair pavilion was quite simple: the pavilion should be an iconic structure capable of seating approximately 300 people, primarily to be used for book readings, presentations and events. It should also allow some flexibility in terms of the use of the space. Another requirement was that the temporary structure should be capable of being erected and dismantled within a short space of time, and subsequently stored, then re-used annually over at least the coming 10 years. The approach to this project was inspired by another schneider+schumacher design – the Autobahn chapel in Siegerland, Germany. It was the inner dome of this chapel (Fig.2) that offered a starting point for the design process for the Book Fair pavilion, officially named the 'Frankfurt Pavilion'. In the Autobahn chapel the dome is constructed as a waffle system of intersecting wooden ribs, and it is a grid in plan, hence the structure is comparatively simple.

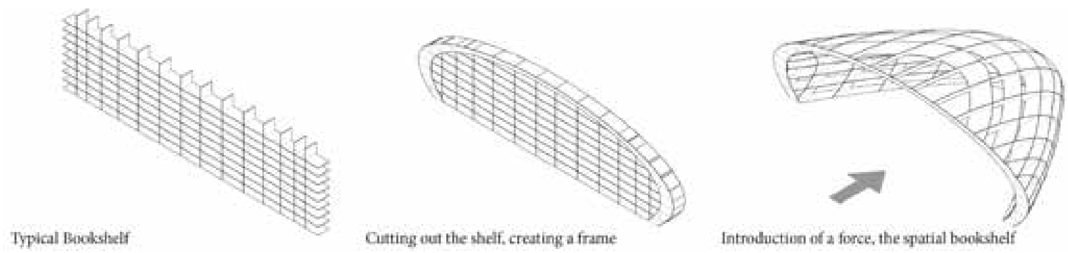

FIG. 3 Spatial transformation of a typical bookshelf into pavilion bookshelves

The design of the Frankfurt Pavilion, on the other hand, sought to amalgamate not only the notions of architectural space and a structural system, but also the philosophical connotation of a space which is intended to house book-related events. This involved experimenting with reinventing the concept of the bookshelf. As shown in Fig.3, a conventional bookshelf was subjected to an imaginative force, which then created a shell, thereby also transforming the bookshelf in the horizontal direction, such that it follows the contours of the inside of the shell. This strategy brought with it a number of challenges, such as how to define the form, ensure structural stability and find appropriate materials, but also with regard to aesthetics, stability and durability. As Sanford Kwinter (Kwinter, 2006) comments in his essay entitled 'The judo of cold combustion': "The new materialism may well be the new expressionism.", the design process of the pavilion strives towards finding a point where form, structure and material fuse together to create a single homogenous entity.

3 OPTIMIZATION – CREATING A HYBRID CONSTRUCT WITH GEOMETRY, STRUCTURE AND SKIN

3.1 GEOMETRY

The geometrical design of the pavilion is based on a simple principle of three identical shells, which together intersect to create a single space. The building envelope consists of three structurally independent, identical, monocoque systems that integrate the outer layer and its structural behaviour in one single-layered envelope. Employing a vertical grid to generate the waffle-like structural frame, means that horizontal ribs are created too, and these can also function as bookshelves, thereby integrating a third function within the building envelope as shown in Fig.4.

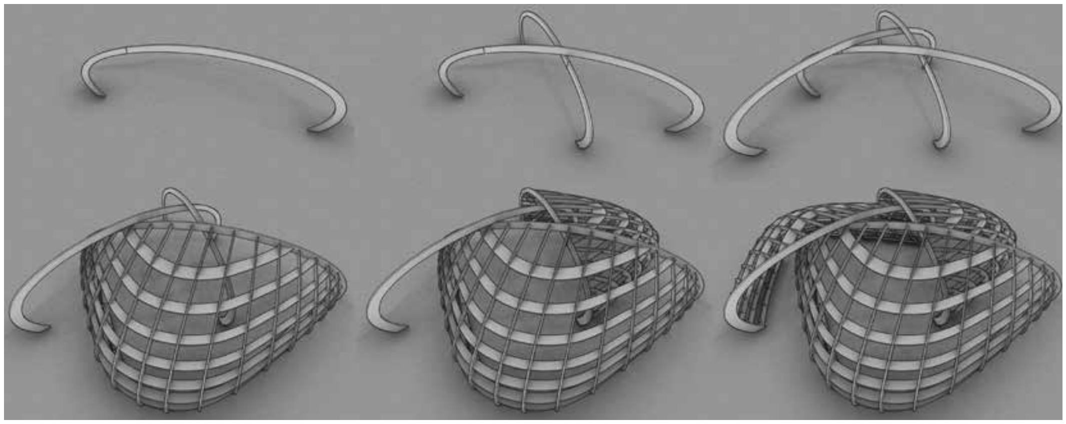

FIG. 4 Design logic of the pavilion

Contemporary architecture employs digital tools in design, analysis and production and these digital aids are helping to break down the linearity of conventional architectural processes. By using a combination of various computational tools it has now become possible to create a more fluid interactive process between the various contributing factors that produce an efficient and optimal design solution. The authors of this paper have been researching various aspects of integrated design systems over the past few years. In several schneider+schumacher projects they have focused on the potential and the limits of fluid design systems that combine feedback logic between geometry, structure, and materials. Among such experiments in this series is the bus-stop shelter "Parapluie". Here the limits of Ultra High Performance Concrete (UHPC) was tested so that, by combining geometric effects in form, and material effects in structure, the ultimate form resulted in a very thin concrete shell (Eisenbach, Vasudevan, Grohmann, Bollinger, & Hauser, 2014).

3.2 COMPUTATIONAL INTEGRATED SYSTEM

For the Frankfurt Pavilion, a computational system was created to control the overall geometry, employing the simplest parameters. By constructing just one shell and then triplicating the system, only one shell had then to be analysed (see Fig.4). At the same time, the client's spatial requirements were kept carefully in check throughout the process. Since the three shells are identical, a single lateral displacement plus a rotation of 120° and 240° generates the entire space, and three entrances result from this displacement and rotation. The shell itself is a part of a larger geometry that is controlled by tangents and their intensities (see Fig.5). The upper three images show the global geometry and the resultant shell as part of it. The diagram describes the logic of the creation of the form. The two curves are generated by vectors (va1 and va2 for the outer surface and vb1 and vb2 for the inner surface). The angle of the vectors va1 and vb1 to the horizontal are 'a' and 'b' respectively, and the system is built with the condition that b > a. The difference in the angles then also defines the structural cross-section depth at the thickest part of the rib. The combination of vector intensities and vector angles were the controlling parameters for the geometry of the pavilion. The outer curve subsequently also defines the geometry of the skin. This is one of the key integration aspects, since both structure and skin are defined by the same parameters. As a result, the system is capable of responding to minor changes so as to get the maximum out of the form and the material. A computational system needs to be designed to function responsively and efficiently in an integrated geometrical and structural system. This requires ensuring that the basic aspects of constraints, constants, variables, their interrelationships and hierarchies are fluidly controlled, so they are capable of maintaining the system responsive at all limits of the variables.

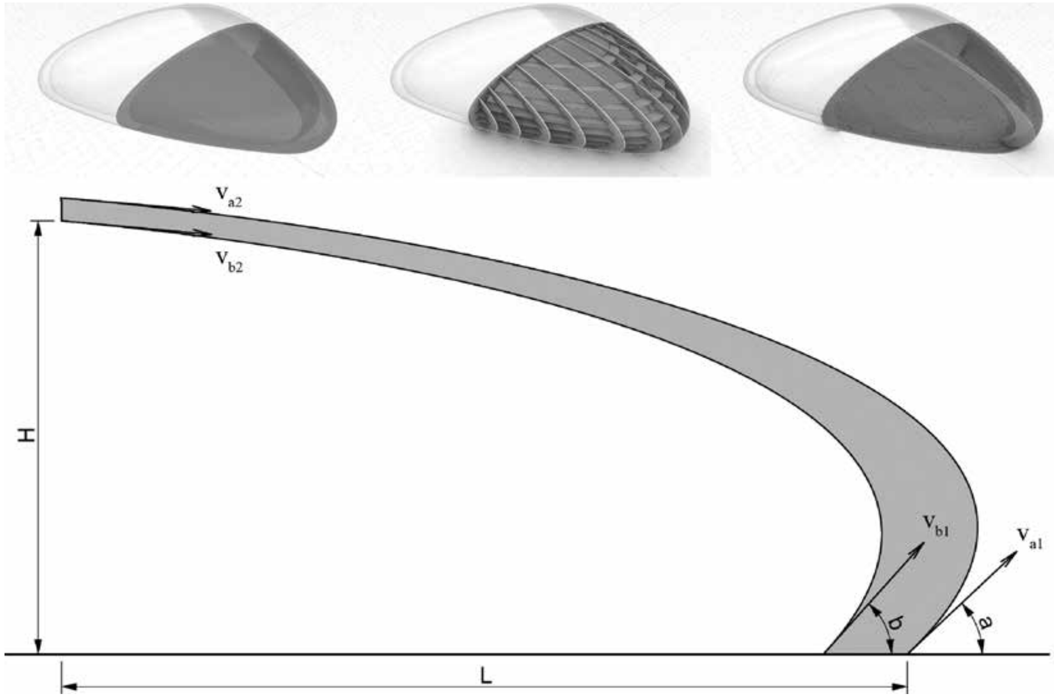

FIG. 5 Geometric system and controlling elements of the base geometry

A detailed explanation of such a system can be found in a paper on another schneider+schumacher project: "die Welle" in Frankfurt. In that project, double curved geometries were produced with roll bent aluminium plates. An ideal parametric system is clearly defined in the paper as follows:

"A parametric design system is a 3D mathematical model based on the various parameters of the design. The basic aspects of such a system are:

- Constants (relating to the design geometry and existing aspects in the site)
- Variables (the values that allow adjustments to the design)
- Interrelationships between the constants and variables
- Hierarchies between the interrelationships
- Boundary conditions (aspects from the site that restrict the design)

A parametric system is hence a combination of the design ideas imbibed into a geometric system with the aforementioned aspects as the basis of the system. The effectiveness of such a system is dependent on the possibilities offered by such a system to test various alternatives under different conditions so as to have a better understanding of the design." (Vasudevan, Fahlbusch, Schumacher, Bollinger, & Grimm, 2016). This is crucial when the system is put through an optimization process. For the pavilion, the aforementioned logic was used to build a computational system that could be controlled by a minimal number of parameters. This ensured the stability of the system at all stages during the optimization process, which enabled a maximum number of variations to be tested, thereby producing a more diverse set of results.

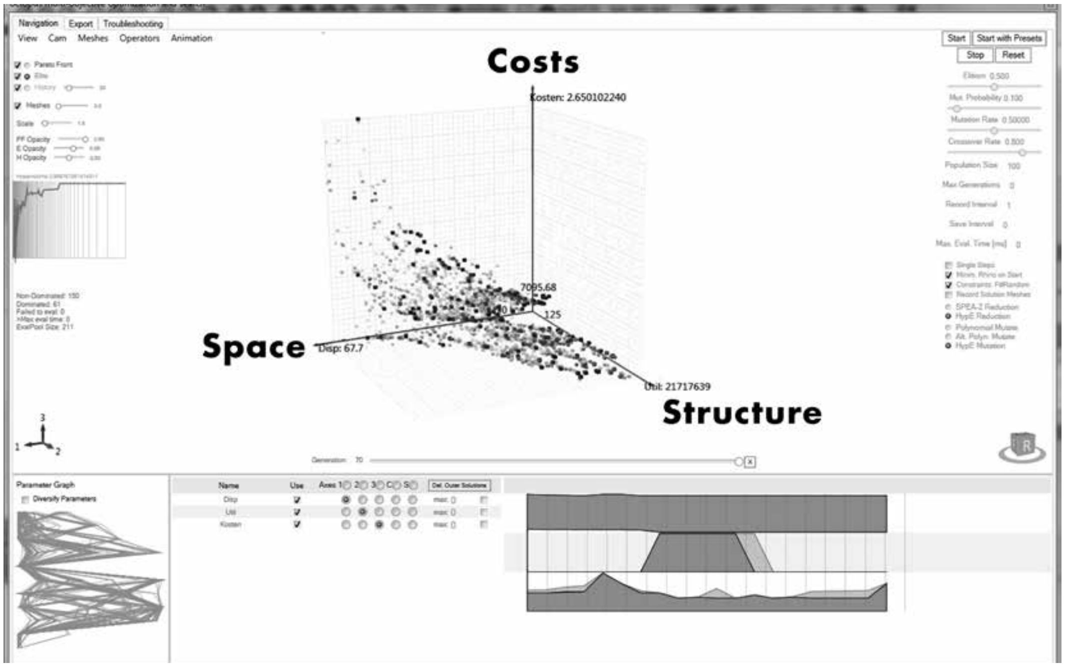

FIG. 6 The multi-objective optimization in Octopus

3.3 OPTIMIZATION THROUGH EVOLUTIONARY MATHEMATICS

In the case of the pavilion, optimization was done using a 3-axes system for specific fitness criteria based on evolutionary analysis with a tool called Octopus (Vierlinger, 2014) for Grasshopper – a visual programming tool developed for Rhinoceros as shown in Fig.6 and Fig.7.

The first of these three axes was the parameter of the spatial requirement for 300 seats. Since the number of seats was integrated in the system, this could be verified with every iteration. The second axis was based on the results from the structural analysis of the geometry. This was integrated in the Grasshopper system with the help of a tool called Karamba3D, a plugin for Grasshopper developed by Clemens Preisinger in cooperation with Bollinger+Grohmann ZT GmbH in Vienna (Presinger, 2013).

The structural analysis for the pavilion was integrated by the structural engineers in such a way that any variation in the original geometry would be visible as a related consequence in the structural stability of the system. To analyse the structural stability in Karamba, all influencing factors were incorporated in the various load cases. This meant that the correlation between the wooden rib structure and the tension on the structure introduced by the membrane could be constantly checked and verified for every iteration. For the optimization process, a single fixed relevant combination of load cases was chosen in which self-weight, wind load, and membrane pre-stress were all taken into account. Specific fitness criteria consisted of structural aspects, such as the maximum deflection and the average maximum utilization of each set of members. The third axis for the fitness criteria was cost, as determined by the various geometrical elements. All the partners involved in the project participated throughout the entire development process. This included the consultants as well as the production companies – Holzbau Amann GmbH for the wooden structure, and Taiyo Europe GmbH for the membrane. This meant that detailed information on factors that might affect the final cost of the pavilion was constantly available. It was thus possible to include cost as a factor in the optimization process.

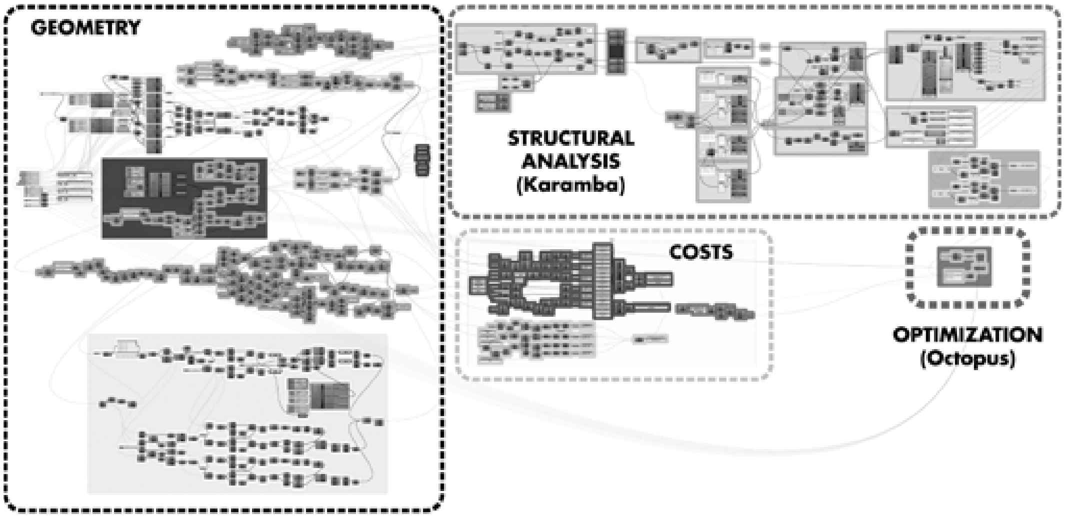

FIG. 7 The parametric system in Grasshopper

Fig.7 shows the combined parametric system, where the geometry of the pavilion, the structural analysis and the costs are all combined and influence one another in multiple feedback loops within the system. The optimization in Octopus works inside these feedback loops, analysing the pavilion with evolutionary mathematical algorithms in a multi-dimensional iterative process. During this process various combinations of variables are tested with each other and a large set of variations are produced and cross-analysed. Results that tend towards a more optimal solution then form the basis of the next generation. These iterations are then repeated until the solutions tend towards an optimal junction of all three pre-defined fitness conditions. This process has been well described by David Rutten in his work on evolutionary solutions for parametric design in Grasshopper (Rutten, 2010).

3.4 MATERIALISING THE OPTIMIZED GEOMETRY

The pavilion's structural ribs are cut out of laminated veneer lumber (Kerto-Q) with a weight of 510 kg/m^3. The three main arches (Fig.4) have cross-section thickness of 150mm. The ribs are built up in sizes as large as possible within the limits of standard transportable dimensions. The 14 vertical ribs for each shell have a cross-section thickness of 75mm and the 9 horizontal layers have a thickness of 50mm.

The resulting structure is extremely lightweight. Due to the dimensions of the vertical ribs, it was not possible to cut them out of a single plate. This meant that the ribs had to be subdivided, which then implied that the fibre direction would change along the length of the rib. The consequence of this change in fibre direction was a reduction in structural stability at the junctions. This meant that in the structural analysis thorough consideration had to be given to the material properties of the varying fibre directions along the length of each rib (Fig.8).

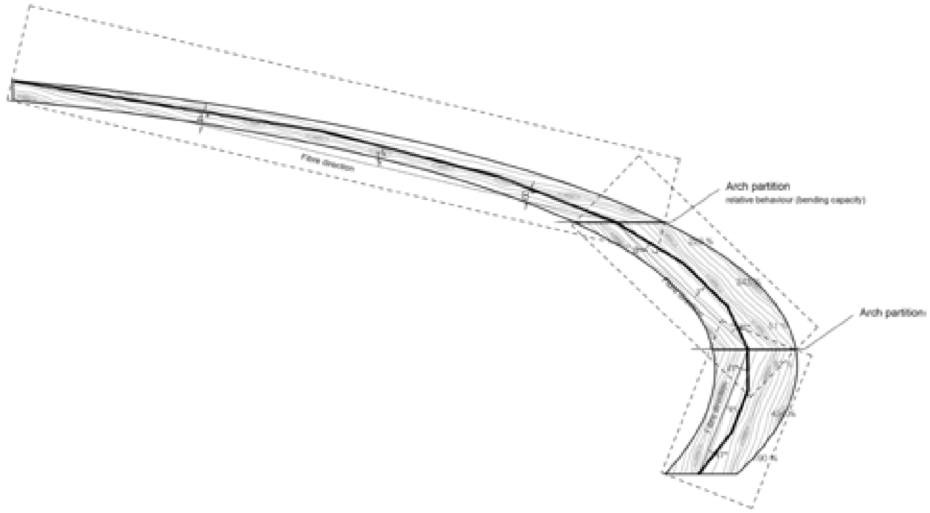

FIG. 8 A vertical rib showing sub-divisions, fibre directions and organization of the parts in the plates.

The pre-stressed membrane is made of PVC and produced by Taiyo Europe. The membrane forms the skin and also provides tension across the wooden members, thus keeping the entire structure stable. This membrane is fixed only to the main arch and to the floor. This means it glides over the intermediary ribs, thereby conveying its tensile strength only to the vertical ribs. The horizontal ribs are offset towards the inside, so they do not come into contact with the membrane. This creates a hierarchical system of dynamic force transfer throughout the system, as any element from one group of structural members is only in contact with the next group of structural members (Fig.9).

This ensures the durability of the individual elements and also reduces the possibility of wear and tear through minimised contact with the structural elements. Since the membrane is elastic and the wooden structure quite rigid, this hierarchy of elements ensures that the membrane is not damaged by contact and friction with a large part of the structure. This also protects the individual elements when the pavilion is erected and dismantled a number of times.

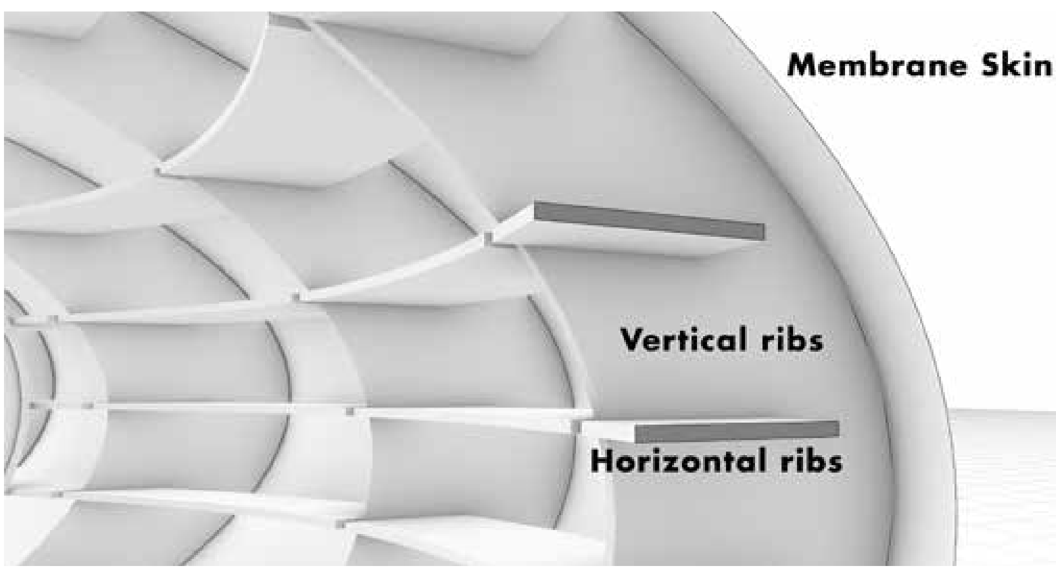

FIG. 9 Detail of the structural ribs and the membrane skin.

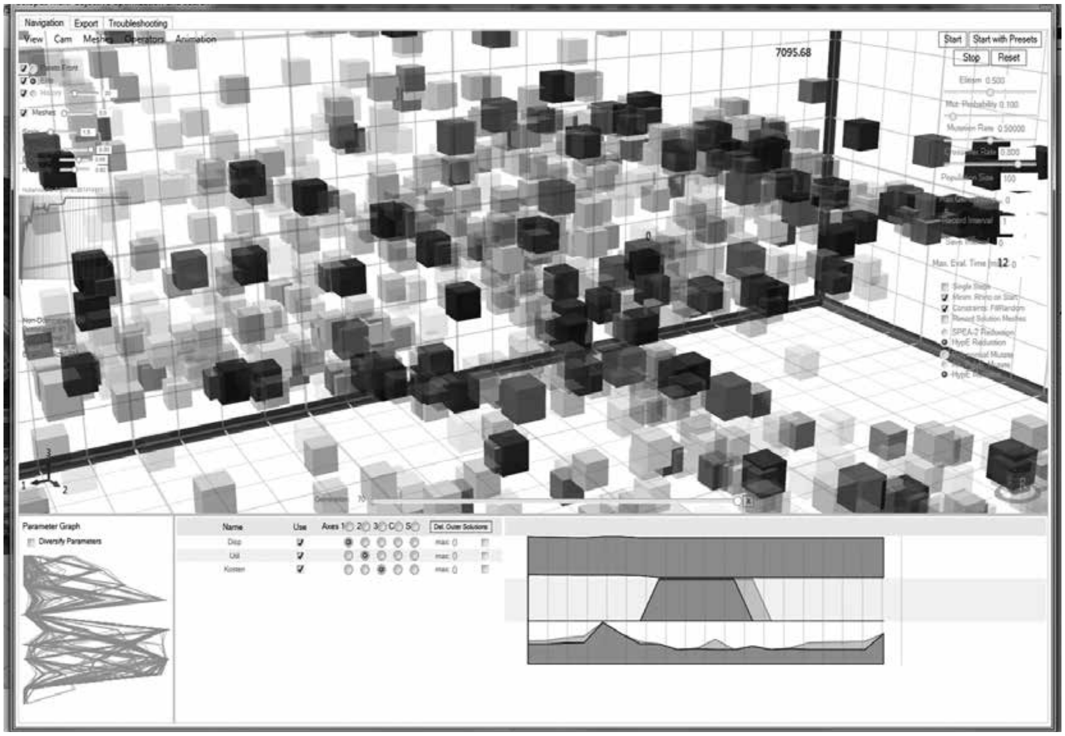

FIG. 10 Typical image of the resulting optimisation

4 RESULTANT GEOMETRY THROUGH OPTIMIZATION

The entire optimization process was an autonomous procedure, which was carried out with a large number of iterations, so all possibilities could be considered before choosing the best one. In order to obtain a meaningful result from this process, it was essential to test the system to the limit, to be sure that during the iteration process, the system would not collapse. This is an essential and important aspect of all such computational systems, since it also defines the maximum freedom of optimization available to the system. It is also essential to keep variables to the bare minimum, since this allows an efficient calculation process that is fast enough to produce quick results. This is also evident from the simplicity of the geometrical logic used in the development of the pavilion. A typical view of the outcome of such an optimization process can be seen in Fig.10.

Once a particular solution has been selected, that solution is activated in the system so one can trace the exact parameters that lead up to that solution. Here it is interesting to note that some of the results were far more surprising than expected, and they deviated substantially from what one might have assumed to be correct. However, having cross-checked the results thoroughly in an independent process based on conventional calculations, it was confirmed that the results obtained from the optimization process were completely correct. It was also interesting to note that the process had pushed the geometry to the absolute minimum in terms of use of material, thereby creating a highly efficient system.

FIG. 11 View of the Frankfurt Pavilion at the Frankfurt Book Fair 2018

5 CONCLUSION

The entire design and analysis process for the pavilion provides an insight into the possibilities that current day computational tools can offer. When used efficiently, they help to reduce the costs of the production process by optimizing the use of material in conjunction with a particular geometrical configuration. Furthermore, such integrated systems reduce the cost of the design process itself by making it much more efficient. By combining all the pavilion elements into a single hybrid system – structure and skin – the resulting form can be regarded as having been optimally integrated. Ultimately such an integrated design system thus offers several advantages – not only in terms of increasing efficiency and saving costs throughout design development and in production – but also in generating spaces that directly reflect the process by which they were created. In October 2018, this process was tested in its entirety at the Frankfurt Book Fair 2018. As can be seen in Fig.11 and 12, the process described in this paper was executed successfully, which affirms the ideas that the authors set out to experiment.

FIG. 12 Interior view of the Pavilion at the Frankfurt Book Fair 2018

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One-and-a-half skin glass facade

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Abstract

Premise: why we chose a compromise between a single skin and a double skin facade. Double skin facades are very popular and offer advantages over the "single skin" that can be synthesized in: greater efficiency in summer and winter, the ability to accommodate protected mobile shielding systems and maximize natural light and transparency. These advantages are countered by disadvantages that are essentially the result of increased space consumption and higher costs. In temperate climates, characterized by mild winters and hot summers, the cost of double skin is generally not compensated by the advantages it offers.

Aim : having the advantages of a double skin without the disadvantages. A dynamic facade, using glass and curtains, was designed for a specific project on a small conference room, in an office building in Rome. Regarding the facade, the objectives of the project were to have the maximum possible transparency of the glazed volume and the possibility of integrating systems to partially shield or obscure the room. At the same time, allowing the air space to be used most of the year.

Ambitions - the design of a one-and-a-half skin facade. During the summer months, the facade of the building receives only a few hours of direct radiation in the morning, then the adjacent buildings create shade. This condition made it possible to conceive a volume with a large glass surface, a solution that in a different condition, with greater irradiation, would have been difficult to achieve in Rome. The first skin is a glass facade, while the inner skin is made up of two roller blinds overlapping to form a 60 cm air space. The curtains are made of interwoven narrow mesh fibre sheets, the first is white fibreglass with a high reflecting power and diffusing light, the second is carbon fibre with a high darkening power. In winter, the curtains are used only to diffuse the light inside or decrease the level of lighting. In summer, the curtains are lowered and generate the air space. The vents, placed on the floor and at the top, open generating an upward flow of air that expels the accumulated heat. When the temperature in the air space increases, the flow of air from natural first becomes forced and then, to further increase the heat exchange, the air is cooled.
A preliminary investigation on the facade behaviour in the passive asset has been conducted. Several configurations have been investigated to evaluate temperature values in the room and in the gap, with or without natural ventilation and different type of curtains. Considering various combination with fixed external condition and no mechanical system. The project is in progress and since we have a real building, this case study will be furthermore investigated; a in-field monitoring survey, to measure the relevant environmental parameters, is being planned. A more in-depth analysis, with the energy simulation of the building and the estimate of energy savings, will be carried out in combination with the indoor environmental monitoring, as a second step of the research.

Keywords

Double skin, curtains, dynamic facade

1 INTRODUCTION

Why create a compromise between the single skin and the double skin facade. Double skin facades are very common and offer advantages over "single skin" facades, which can be summarized in greater thermal efficiency in winter, and in summer the possibility of hosting protected mobile shielding systems, thus maximizing the natural light and transparency of the glass facade. These advantages are contrasted with disadvantages that essentially consist of a greater consumption of space and higher cost due to both the doubling of the surface area of the facade and the need to have more sophisticated control systems for ventilation and shielding. In temperate climatic contexts such as those of the Mediterranean, characterised by mild winters and hot summers, the cost of double skin is generally not repaid by the advantages it offers.

To maximize both winter and summer benefits, facades have become dynamic. With the inclusion of sensors and actuators a facade can become "responsive" serving as an interface between the user in the building and the climate outside. "Nowadays it's possible to automate almost all processes of building operation. Optimizing the way a building is operated can provide energy savings but it can also result in unintended overconsumption" (Hausladen, Saldanha, Liedl, 2005). The insertion of substituted automation systems, however, entails an increase in costs and reliability problems for the operation of these systems over time. The interfaces that manage the building automation can become complex, and in cases of incorrect use or malfunctioning of the sophisticated systems, these can become useless or harmful systems.

In order to reduce energy consumptions and increasing comfort level in buildings, passive ventilation strategies can be applied (Jing, Chen, Li, 2015) and (Jyotirmay, Bansal, Sanjay, Meenakshi, Anupma, 2006). Several investigation have been conducted, both numerical and experimental, on application involving building envelope, such as solar chimneys and ventilated facade (Ong, 2003) (Zanghirella, Perino, Serra, 2011). In this study the feasibility and performance of a similar system, but where the glass facade is coupled with a movable curtain, thus forming an air gap, naturally ventilated, are investigated (Sanchez, Rolando, Ayuso, Sant, 2016) and (Flores Larsen, Rengifo, Filippin, 2015).

Our aim is to have the advantages of a double skin without the disadvantages.A specific project for a small conference room in an office building in Rome, a dynamic facade using glass and curtains was designed.

FIG. 1 The new Ghella Meeting Centre building, nestled between two pre-existing buildings

The objectives of the project, with regard to the facade, were to have the maximum possible transparency of the glass volume avoiding external shading system, and the possibility of integrating systems to screen or partially obscure the room. Given the small surface area available, a system was designed that could be similar to a double skin when necessary and when not necessary leave all the space free. The use of curtains creates a subdivision of the space into two distinct climatic zones, the area next to the facade, which is a band of about 60 cm deep with its own ventilation, and the remaining surface of the room, also with its own ventilation and air conditioning. This condition occurs only when the climatic conditions due to the radiation require it, for the rest of the time the curtains are rolled up and the surface is all usable.

This system could be useful and adoptable in other situations where the loss of space and the increasing cost of a double skin are non acceptable by the client, and the lack of external shading system is an architectural issues.

2 METHODOLOGY

The facade project. In the summer months, the facade of the building receives only a few hours of direct sunlight in the morning, then the adjoining buildings provide it with shade. This condition allowed us to conceive a large glazed volume, a solution that in a different condition with greater irradiation would have been difficult to achieve in Rome.

The glass on the facade covers the entire front and also continues to cover a depth of about one meter, so as to hide the thickness of the floors and give an "all glass" image. The facade has no openings and is supported by a structure in stainless steel I 120 profiles. Each glass has a size of 140 x 540 cm. At the base of the facade and at the top there are openings with "flaps" that regulate the entry and exit of the air.

The functioning of the facade is managed by a Building automation system that refers to the different scenarios the room may be used for: normal use, projection, or when empty. Unless specific requests such as projection are made, the system opens and closes the blinds according to the temperature measured at the top of the inside glass. At the same time, the system opens or closes the lower and upper flaps for ventilation of the cavity and, if necessary, activates cooling of the cavity by means of dedicated fan coils. To ensure optimal comfort conditions in the occupied space, a mechanical system provides cooling and air exchanges. In detail, a mechanical external air ventilation system balances latent loads and ensures air exchanges. For thermal/cooling and internal loads fan coils have been provided in the room, to be activated wen facade system is not sufficient.

The shading system consists of two blinds, one darkening and one partially reflecting; these allow to regulate the daylight, until total obscuration, and the diffusion of the light, so as to avoid glare.

The project was developed in BIM and this allowed to manage the complexity of execution of many components compressed in a small space, integrating the systems, structures and facades in an optimal way.

The building is currently undergoing LEED.v4 BD+C certification and is currently almost completed.

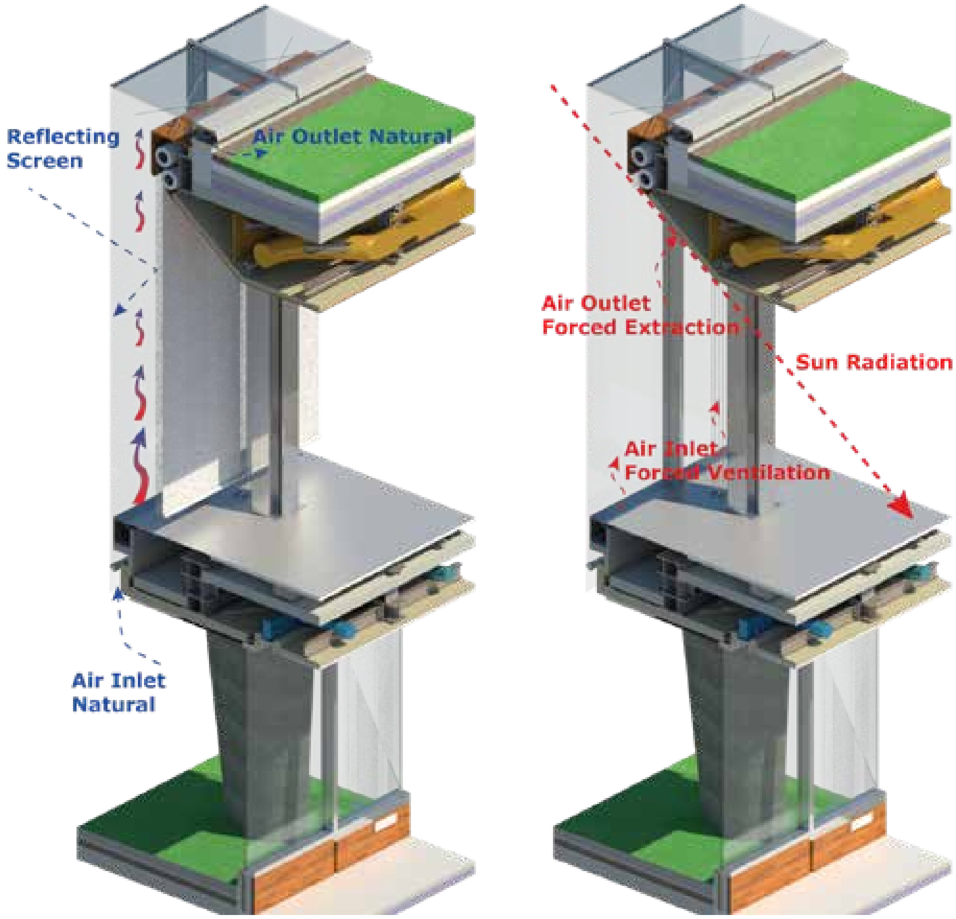


FIG. 2 SUMMER left operating scheme with closed awning (radiation protection) WINTER right scheme with raised awnings (thermal radiation gains)

To study the feasibility of the proposed system, a preliminary investigation on the facade behaviour in the passive asset has been conducted. In the investigated configuration, upper and lower ventilation openings have been inserted, through grilles placed on the floor and on the roof, along the edge facade.

A curtain system has also been placed in this configuration, to confine the glazed area, where most of the heat exchanges occur, and where natural ventilation is located.

Several configurations have been investigated.

- Glass facade, no ventilation
- Glass facade + natural ventilation
- Glass facade + natural ventilation + opaque 'black' curtain (high absorptivity coefficient in the whole spectrum) or glass facade + natural ventilation + opaque reflecting curtain (high reflection coefficient in the whole spectrum)
- Glass facade + natural ventilation + both curtains very close to each other (no air gap between them).
- Glass facade + natural ventilation + partially transparent curtain.

Heat exchanges have been evaluated, and through an energy balance for each configuration, have been estimated:

- Room temperature
- Curtain temperature
- Air flow rate
- Thermal power removed by air
- Average temperature in the gap between glass and curtain.

Mathematical model results will be compared with those coming from an environmental monitoring activity. Temperature and air velocity sensors will be placed on the sides and in the middle in the air gap, at three different heights, to evaluate the temperature value and its uniformity, and the air velocity/flow rate value. Temperature sensors will also be placed in the room and outside. Solar radiation will also be monitored and detected. The measured values will be detected continuously, at the same time the operation and the activity carried out in the room (number of people, appliances and lamps, curtains operation, etc.) will be recorded.

3 RESEARCH

3.1 ANALYSIS

Air ventilation benefits with and without curtains adoption, in a room with a glass facade under given direct solar radiation have been investigated through the evaluation of the heat removed by external air inlet and outlet, and of the room air temperature; internal loads have not been considered.

Night ventilation is a useful strategy to precool space, and it is made possible in the configuration adopted by the presence of ventilation grids; it would certainly bring a benefit, that however has not been considered in this preliminary work, limited to the evaluation of the facade system potential, and therefore conducted on the basis of precautionary hypotheses in order not to overestimate possible benefits.

Given that, in each configuration investigated, a unit width facade has been considered, with height H=3,5 m; room depth is W=6 m; the other external room walls have been considered opaque, with overall heat transfer coefficient UROOM=0.3 W/m^{2}K, and absorptivity coefficient awalls=1; a sun radiation WINC=400 W/m2 has been considered. The external air temperature value is assumed tEXT=25°C.

External surface heat transfer coefficient is assumed kE=20 W/m^2°C. Convection coefficient between curtain and air in the room has been assumed hC=3, while inside the gap between glass and curtain depends on air velocity.

Radiation heat transfer coefficient is calculated on the basis of radiative properties of the surfaces.

For the glass facade, a selective insulating double pane glass, has been considered, because of the typical design choice of sunscreen glasses in wide glass facades, in Mediterranean climate. It has been considered sun radiation, especially infrared radiation, mostly absorbed by the outer

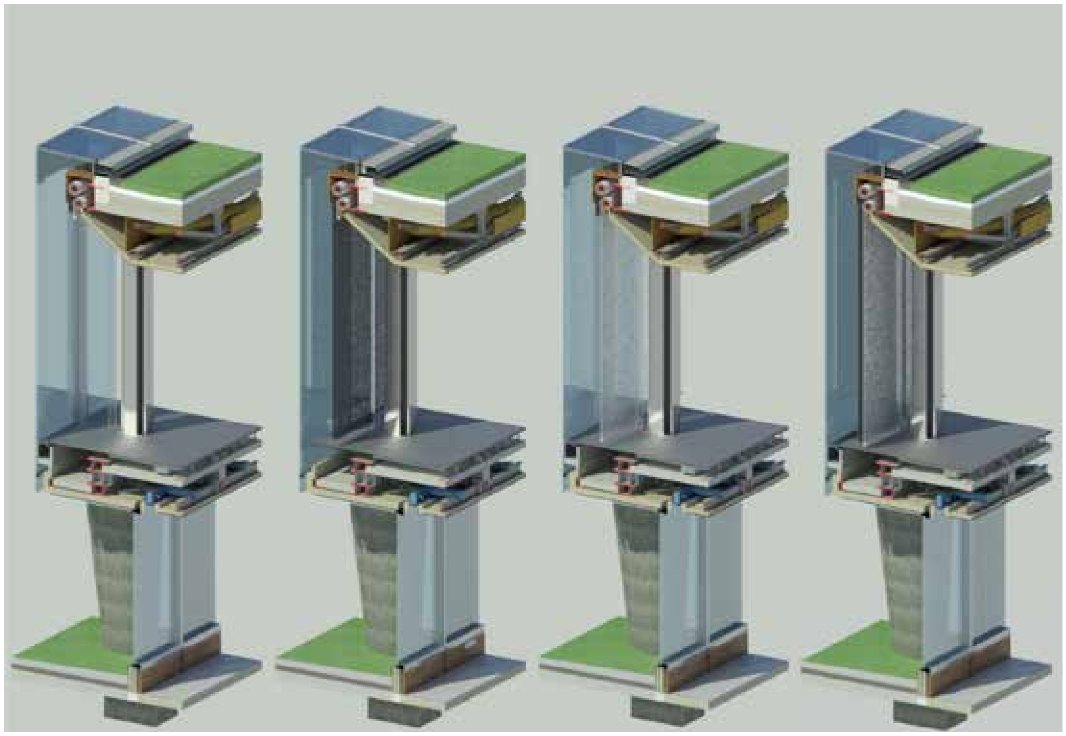


FIG. 3 The different facade configurations from left 1 - without blinds 2 - lowered blinds 3 - lowered reflective blinds 4 - both lowered black and white blinds

pane, and in a minor part, included essentially in the visible spectrum, transmitted to the inner pane and then into the room. In detail, the glass solar factor is SF=0,23. Glass overall heat transfer coefficient is UG=1,3 W/m^2°C.

Different cases have been investigated, also with reference to the radiative properties of the curtains. For both cases of black and reflecting curtains, opaque curtain and partially transparent curtain cases have been considered. Curtains have always been considered as grey-body surfaces.

The first skin is a glass facade, while the inner skin is made up of two overlapping roller blinds to form a 60 cm gap. The curtains are made of 6mm thick interwoven narrow-mesh fibre sheets, the first of which is made of white glass fibre with a high reflecting and diffusing power, the second of which is made of carbon fibre with a high darkening power. In winter, curtains are only used when it is useful to diffuse light inside or decrease the light level. In summer, during the hours of radiation, depending on the use of the room, the curtains are both lowered and generate the cavity. The vents placed on the floor and at the top open generating an upward flow of air that expels the heat accumulated, when the temperature in the cavity increases, the flow of air first of all from natural becomes forced, and then, to further increase the disposal of heat, the air is cooled.

The technology used to make the curtains comes from the production of sails for the boating industry, which has allowed us to make sheets of 550 x 400 cm in a single sailcloth, the sheets are made using impregnated fibres woven with CNC machines. In our case the fibres chosen were the Glass fibre for its characteristics of reflection and light diffusion and the Carbon fibre for its characteristic of obscuring. The narrow texture of the fibres increases the coefficient of reflection (thermal reflectance 70%) and reduces the passage of air through the sheets (permeability 25%).

3.2 MATHEMATICAL MODEL

Under these assumptions, heat exchanges have been examined in several cases. Heat balance equations have been applied in this simplified approach; the model validity and results will be validated through an environmental room monitoring.

As already described, various cases have been studied.

1 Empty room, no curtains.
In the first case the room without curtains, both without and with natural ventilation, has been investigated, as sketched in Fig.4 and 5.

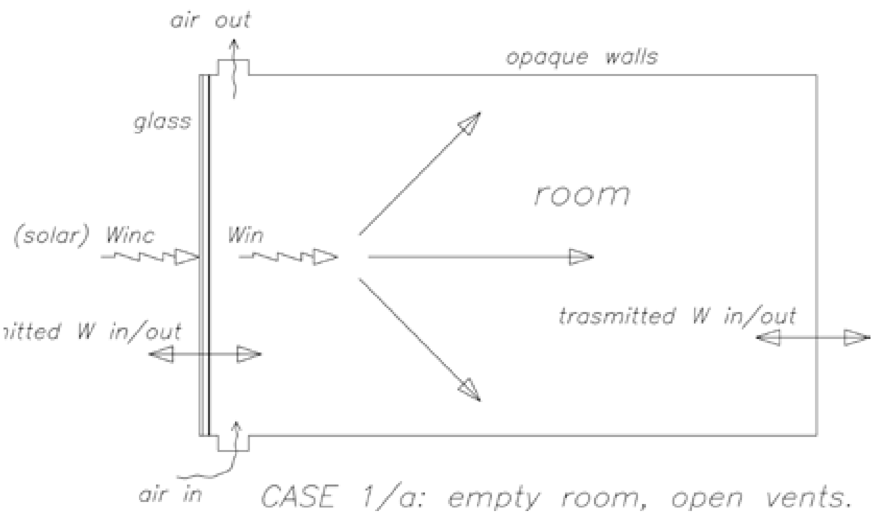


FIG. 4 Case 1/a - empty room, open vents

- Room heat balance

$$W_{INC} = W_S \cdot H \quad (1)$$

$$W_{IN} = W_{INC} \cdot SF \cdot a_{walls} \quad (2)$$

$$W_{OUT} = H \cdot U_G \cdot (t_{ROOM} - t_{EXT}) + q_{AIR} \cdot \rho_{AIR} \cdot c_{Pair} \cdot (t_{ROOM} - t_{EXT}) + A_{ROOM} \cdot U_{ROOM} \cdot (t_{ROOM} - t_{EXT}) \quad (3)$$

$$W_{INC} = W_{OUT} \quad (4)$$

- Airflow balance
Assuming uniform temperature t_{ROOM} and density 〉 in the room:

Stack pressure $$\Delta P_S = \frac{t_{ROOM} - t_{EXT}}{t_{EXT} + 273.2} \rho g H \quad (5)$$

Pressure loss $$\Delta P_L = 2 \cdot \left\{ [\rho_{IN} c_{IN} \frac{(q_{AIR} / A_{IN})^2}{2} + \rho_{OUT} c_{OUT} \frac{(q_{AIR} / A_{OUT})^2}{2} \right\} \quad (6)$$

$$\Delta P_S = \Delta P_L \quad (7)$$

Were c_{IN} and c_{OUT} are the inlet and outlet pressure loss coefficients of each vent; A_{IN} and A_{OUT} the inlet and outlet areas.

— Heat extracted by air flowing; being $t_{OUT} = t_{ROOM}$

$$W_{AIR} = q_{AIR}\rho_{AIR}c_{Pair}(t_{ROOM} - t_{EXT}) \quad (8)$$

Assuming first guessed values of t_{ROOM} the system of equations (1-8) has been solved by iteration

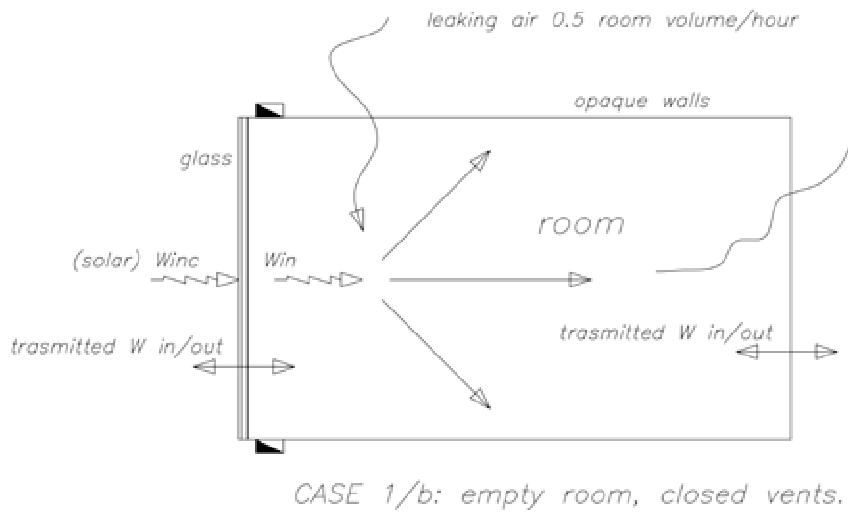


FIG. 5 Case 1/b - empty room, closed vents

It is assumed a natural air change by leakage of 0.5 room volume/hour

$$q^*_{AIR} = 0.5 \cdot V_{ROOM} / 3600 \quad m^3/s$$

— Room heat balance

$$W_{INC} = W_S \cdot H \quad (9)$$

$$W_{IN} = W_{INC} \cdot SF \cdot a_{walls} \quad (10)$$

$$W_{OUT} = H \cdot U_G \cdot (t_{ROOM} - t_{EXT}) + q^*_{AIR} \cdot \rho_{AIR} \cdot c_{Pair} \cdot (t_{ROOM} - t_{EXT}) + A_{ROOM} \cdot U_{ROOM} \cdot (t_{ROOM} - t_{EXT}) \quad (11)$$

$$W_{INC} = W_{OUT} \quad (12)$$

Heat extracted by air leakage outgoing, being $t_{OUT} = t_{ROOM}$

$$W_{AIR} = q^*_{AIR}\rho_{AIR}c_{Pair}(t_{ROOM} - t_{EXT}) \quad (13)$$

Again, assuming the first guessed values of t_{ROOM}, the system of equations (9-13) has been solved by iteration.

In the following cases the room with curtains, with natural ventilation, has been investigated, as sketched in Fig. 5. Different cases are obtained varying opportunely radiative properties of the surfaces involved in the heat exchange balances.

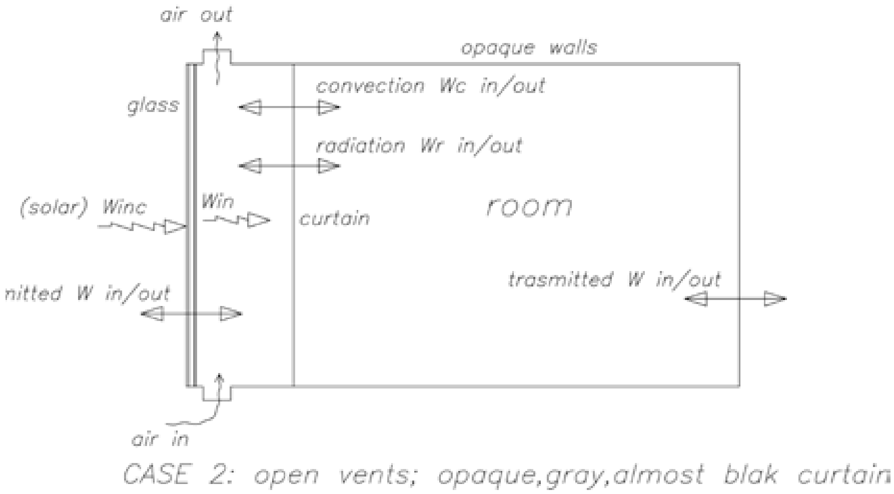


FIG. 6 Open vents, curtain opaque, grey, almost black, in front of the glass, so forming a solar chimney.s

- Curtain heat balance

$$W_{IN}^{C} = W_{INC} \cdot SF \cdot a_{CURT} \tag{14}$$

$$W_{OUT}^{C} = H \cdot [h_{CC} \cdot (t_{CURT} - t_{AV}) + U_{GR}(t_{CURT} - t_{EST}) + K_I(t_{CURT} - t_{ROOM}) \tag{15}$$

It must be

$$W_{IN}^{C} = W_{OUT}^{C} \tag{16}$$

t_{CURT} is the average value of the curtain temperature; aCURT=0,95.

- Airflow balance in the solar chimney

It is assumed linear variation of air temperature in the chimney from the floor (air in) to the ceiling (air out). Then the average air temperature in the chimney is

$$t_{AV} = \frac{t_{EXT} + t_{OUT}}{2} \text{ and } t_{OUT} = 2t_{AV} - t_{EXT}. \tag{17}$$

Stack pressure $\Delta P_S = \frac{t_{OUT-}t_{EXT}}{t_{EXT} + 273.2}\rho g H$ (18)

Pressure loss $\Delta P_L = 2 \cdot \left\{ [\rho_{IN} c_{IN} \frac{(q_{AIR} / A_{IN})^2}{2} + \rho_{OUT} c_{OUT} \frac{(q_{AIR} / A_{OUT})^2}{2} \right\}$ (19)

$$\Delta P_S = \Delta P_L$$

Power gained by the air in the chimney (by convection from the curtain and transmission from the external through the glass)

$$W_{IN}^{air} = H \cdot h_{CC}(t_{CURT} - t_{AV}) - U_{GC} \cdot (t_{AV} - t_{EXT}) \tag{20}$$

Power extracted by air flowing in the chimney at the output

$$W_{OUT}^{air} = q_{AIR}\rho_{AIR}c_{Pair}(t_{OUT} - t_{EXT}) \quad (21)$$

$$W_{IN}^{air} = W_{OUT}^{air} \quad (22)$$

Heat balance in the room

$$W_{IN}^{room} = H \cdot Ki \cdot (t_{CURT} - t_{AMB}) \quad (23)$$

$$W_{OUT}^{room} = U_{ROOM} \cdot A_{ROOM} \cdot (t_{ROOM} - t_{EXT}) \quad (24)$$

$$W_{IN}^{room} = W_{OUT}^{room} \quad (25)$$

Assuming first guessed values of t_{CURT}, t_{AV} and t_{AMB}, the system of equations (14-24) has been solved by iteration. Being equations (14-16) and (20-22) mutually linked by the values of t_{CURT} and t_{AV} their values were first relaxed simultaneously; when equation 16 and 22 were satisfied, a new value of tAMB was determined through eq. (23-25) and so on.

The values of UGR and UGC are evaluated from the conductance of the glass CG as follows:

$$U_{GC} = \frac{1}{\frac{1}{K_E} + \frac{1}{C_G} + \frac{1}{h_C}} ; \; U_{GR} = \frac{1}{\frac{1}{K_E} + \frac{1}{C_G} + \frac{1}{h_R}}$$

CG=1,1 W/m2K has been assumed from UG.

h_R is the heat transfer coefficient by radiation and it is evaluated by:

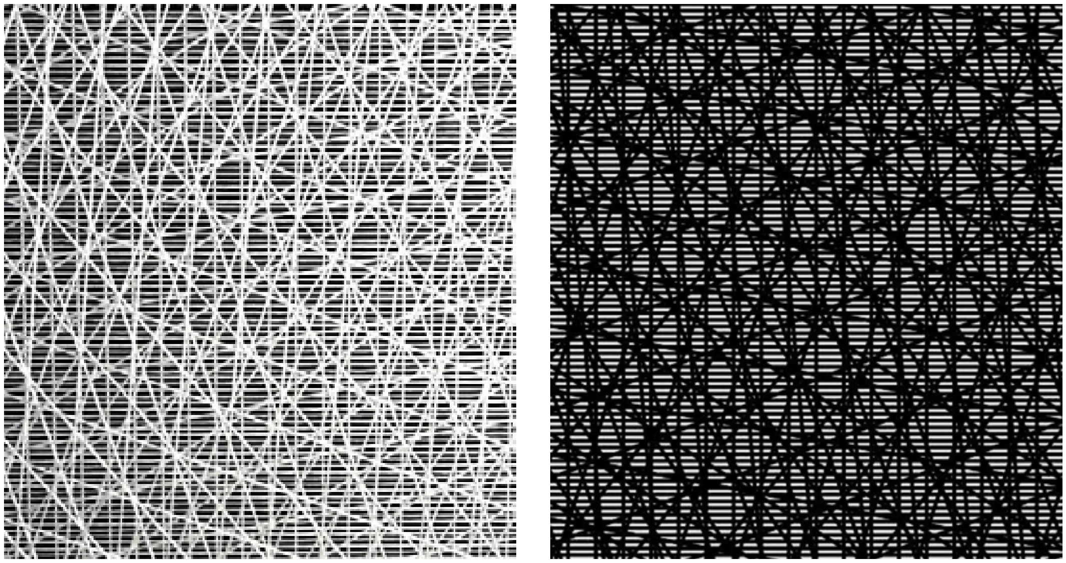
$$h_R = \frac{4\sigma\overline{T}^3}{\frac{1}{\eta_1} + \frac{1}{\eta_2} - 1}$$

where η_1 and η_2 are emissivity coefficients of the surfaces involved in the heat exchanges, and $\overline{T}$ is their absolute temperature values average.

Case 3 - open vents, opaque curtain in front of the glass, so forming a solar chimney; both the facades highly reflecting grey (rC=0.85).

Case 4 and 5 concern the configuration with two curtains, considered in the analysis so close to each other, and at the same temperature.

Case 4 - open vents, opaque curtain in front of the glass, so forming a solar chimney; the curtain toward the glass is grey, highly reflecting; the other one is grey, almost black.



1 2

FIG. 7 The two types of materials for the curtains; left the glass fibre fabric; right the carbon fibre fabric

Two values, rC=0,85 (case 4a) and rC=0.7 (case 4b) have been considered for the reflecting curtain.

Case 5 - open vents, opaque curtain in front of the glass, so forming a solar chimney; the curtain toward the glass is grey, almost black; the other one is grey, highly reflecting.

It has been assumed rC=0,85 for the reflecting curtain.

Case 6, 7 and 8 are related to the use of a reflecting curtain partially transparent to sun radiation, alone or coupled with a black curtain.

Case 6 - open vents, partially transparent highly reflecting curtain in front of the glass, so forming a solar chimney; the other curtain is almost black.

It has been considered a curtain with high reflection coefficient rC=0,85, but with a 40% surface of holes, having a black curtain behind (configuration to be adopted, for example, if it is necessary to reduce natural light in the room).

Case 7, 8 - open vents, partially transparent highly reflecting curtain in front of the glass, so forming a solar chimney.

Curtains with different properties have been considered: high reflection coefficient rC=0,85, with holes on 40% of the surface (case 7), and rC=0,7, with holes on 25% of the surface (case 8).

In all these cases (3-8), the mathematical model is the same as in case 2, with different values of radiative properties, and consequently of radiative heat exchange coefficient.

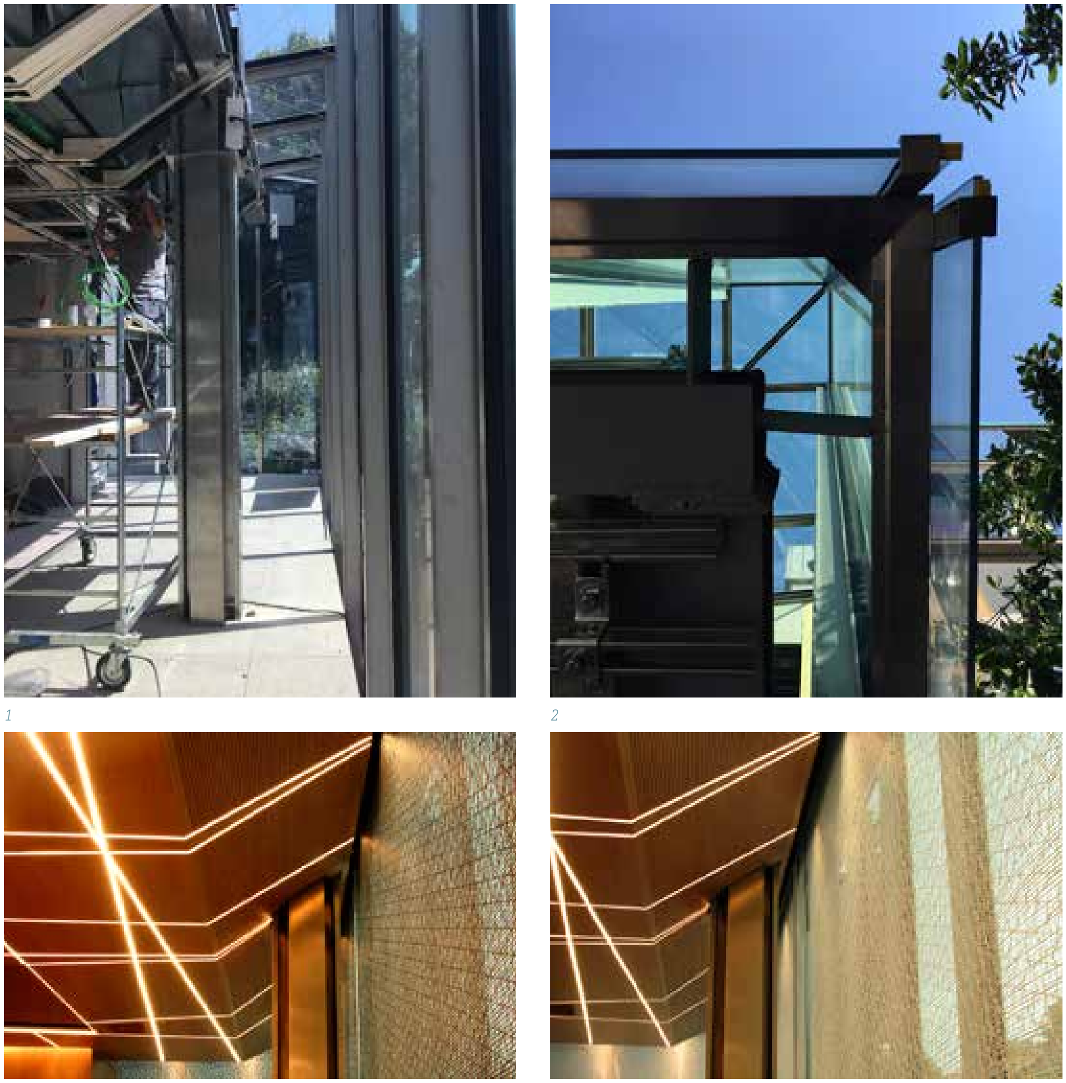
A case with no ventilation and an almost black curtain has been also investigated (case 9) to evaluate benefits from the simple curtain presence.

			TCURT °C	TROOM °C	AIR FLOW-RATE QAIR (M3/S)	HEAT POWER REMOVED BY AIR W/M	TAV °C AVERAGE TEMPERA-TURE IN THE CAVITY
1b	No vent	Empty room	-	53,8	0,0025	86,5	-
1a	Open vents	Empty room	-	29,9	0,055	286,2	-
2	Open vents	Black curtain	33,2	32,1	0,045	171	26,6
3	Open vents	Reflecting curtain	29,7	28,5	0,031	55,6	25,7
4a	Open vents	Reflecting curtain rC=0,85 +black curtain	28,7	28,1	0,029	43,3	25,6
4b	Open vents	Reflecting curtain rC=0,7 +black curtain	29,5	28,9	0,031	53,6	25,7
5	Open vents	Black curtain + reflecting curtain	33,2	32	0,038	99,4	26,1
6	Open vents	Reflecting curtain (40%holes) + black	30,6	29,9	0,042	137,3	26,3
7	Open vents	Reflecting curtain (40%holes)	29,2	36,6	0,036	89,7	26,0
8	Open vents	Reflecting curtain rC=0,7 (25% holes)	30,1	33,1	0,04	116	26,2
9	No vent	Black curtain	38,3	36,5	-	-	43,5

TABLE 1 Examined situation results

4 RESULTS

In cases 6-8 heat exchanges from the room to the window through the holes have been neglected, so temperature values are slightly overestimated. In the investigated cases natural ventilation has been confirmed to be an important strategy to be adopted for energy savings in buildings. In this case study, ventilation grills (coupled with a good sunscreen glass), allow the room air to get a much lower temperature value than in the case without ventilation; this effect can be further improved through the adoption of a curtain with high reflection coefficient. If the reflecting curtain is coupled with a black one behind, room temperature is even lower. This system can also help to avoid overheating of the room when the room is not occupied, thus reducing energy consumptions necessary for cooling. Methodology and equation applied in this study are referred to steady state; they could be applied to non-steady state considering thermal inertia of building envelope and furniture, but non steady state analysis, including precooling with night ventilation, should be conducted case by case, since all the building characteristics, type of use, internal loads, etc., are known.



1 2 3 4

FIG. 8 *The room under construction, to the left the space of the cavity (the curtains will be placed in a plumb line along the pillar) to the right the cavity seen from below (there are still no flaps for the regulation of natural ventilation). Below the black curtain open and both the curtains black and white overlapped*

A more in-depth analysis, with the energy simulation of the building and the estimate of energy savings, will be carried out in combination with the indoor environmental monitoring, as a second step of the research. Here a first approach analysis has been conducted, to estimate how facade characteristics could have influence on internal room temperature.

5 CONCLUSIONS

In specific cases where the use of the entire available surface is important and in a non-continuous use of the environments it is possible to achieve a compromise between the complex and expensive double skin facades and the single facades, putting the internal shielding system in place with an automated ventilation management system.

In this preliminary study the behaviour of such a system has been investigated, considering different configuration an combinations, in presence or absence of natural ventilation and of the various types of curtains, given and fixed the external environmental conditions (summer) and the building characteristic.

Results show that use of internal curtain coupled with natural ventilation of the gap allows to avoid overheating in the room. Indoors air temperature is lower if a reflecting curtain is coupled with a dark curtain. A more in depth analysis, considering also other aspects, such as thermal inertia of the building envelope and furniture, precooling, will carried out together with the indoor environmental monitoring. In fact the project is currently underway and, with a real case in hand, it is planned to make measurements with sensors to verify the design data now obtained through calculations. The use of BIM for the design and control of the construction has helped in the management of a small building very dense with elements and complex construction.

Acknowledgements

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Nomenclature

W_{INC}	Incident power	W/m
W_S	sun power	W/m^2
W	thermal power	W/m
SF	solar factor	
A	area	m^2
H	height of the room	m
U	overall heat transfer coefficient	$W/m^2 °C$
T	temperature	°C, K
ρ	density	Kg/m^3
c_P	specific heat	J/Kg °C
q	airflow rate	m^3/s
c	pressure loss coefficient	
ΔP_S	stack pressure	Pa
ΔP_L	pressure loss	Pa
V	room volume	m^3
g	gravity acceleration	m/s^2
h	heat transfer coefficient,	$W/m^2 °C$
C	conductance,	$W/m^2 °C$
η	emissivity	

4dTEX – Exploration of Movement Mechanisms for 3D-Textiles Used as Solar Shading Devices

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Abstract
Three-dimensional, multi-layer textiles offer specific, constructive-aesthetic possibilities due to their individually adjustable material thickness. They also offer spatially effective modification options via special, still unexplored movement options with low energy input. Movement and the time factor are thus integrated into the textile design as a fourth dimension. Fibre-based high-tech materials have long been used in solid and lightweight construction for reinforcement, solar protection and insulation. In this context, the Textile Lightweight Construction Division of the Frankfurt Research Institute FFin is researching dynamic construction components in combination with textile multilayer structures made of so-called spacer textiles. In the project described below, movement mechanisms for opening and closing or for the control of viewing and incident light from spacer textiles are presented with the aim of developing robust and low-maintenance components for facades. When closed, they can also temporarily reduce energy loss or the heating up of the rooms behind them. Based on traditional sun protection systems such as shutters, venetian blinds and pleated blinds, the FFin is investigating on the one hand the controllable daylight management of multi-layer textiles used as moveable elements as a whole on the macro level, and movements in the textile structure itself, that is to say in the meso level of the spacer textiles on the other.

Keywords
Solar shading, spacer fabric, 3d textiles, dynamic movements, digital textile

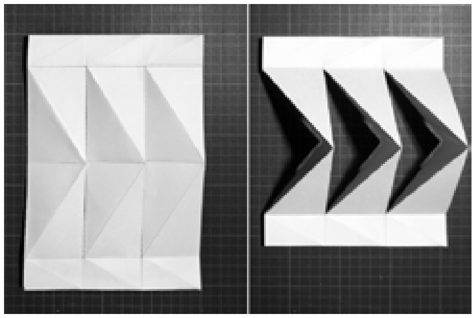


FIG. 1 Origami/kirigami, paper experiment

FIG. 2 Textile folds, Semira Boon

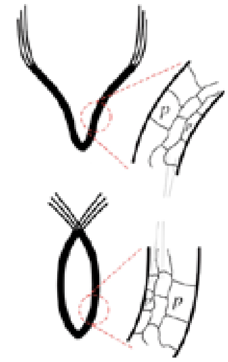


FIG. 3 "Venus trap" principle

1 INTRODUCTION

Over the millennia and often without architects and engineers, solutions have been developed for a wide variety of climate zones for the facade as mankind's active, third skin, both in solid and lightweight construction. They help adjust the comfort level in buildings as required. Building and construction history thus offers sophisticated low-tech solutions that by themselves, however, are no longer sufficient for today's energy and above all electricity requirements. For the future, an intelligent combination of low-tech and high-tech is needed that continues to actively integrate the user in parts and which takes into account local circumstances.

Research is focusing in particular on lightweight and textile construction. Traditional examples such as yurts show the potential of adaptive textile-based lightweight construction solutions for self-supporting wall and roof systems, yurts being perfectly prefabricated, transportable structures with three centimeters of felt skin in summer and an adaptive triple, nine centimeters-thick felt cover against temperatures as low as minus 40°C in winter. This category also includes textile, external solar protection systems as quasi archaic systems in the opening area. Following on from this, technical textiles such as 3D and spacer textiles made from highly-developed fibre materials and manufactured on high-tech machines offer the opportunity to advance the evolution of the building envelope with modern means.

The investigation described below focuses on the most sensitive area of the outer skin of the building – the opening area. The object of the investigation is the extent to which multilayer textiles such as spacer textiles can be used as moveable, possibly adaptive solar protection and at the same time as temporary heat protection. The work is based on the research project "ReFaTex – reversibly foldable, energetically-effective 3D textiles in the building sector" (funding line – Innovationsfonds Forschung). This involves the production of ultra-light and stable elements from spacer textiles in the facade area, which should also be foldable and, depending on requirements, opaque and translucent to transparent. In the course of the research, the term "foldable" was replaced by "moveable" in order to comprehensively capture the dynamic potential of spacer textiles.

FIG. 4 Spacer textile, © Culzean

2 METHODOLOGY

An empirical and experimental methodology was chosen for the research project. At the beginning, experimental investigations with spacer textiles on a 1:1 basis are carried out and optimised by the research team in an iterative process, involving student seminar papers. At the same time, intensive research is carried out on folding technologies, including origami and in combination with kirigami, a paper-cutting art (Fig. 1). In addition, findings from previous research on textile folds on an architectural scale are incorporated (Fig. 2) and inspirations from nature (Fig. 3) included, with soft material transitions, bends, hingeless joints as well as complex unfolding patterns in animals and plants being considered.

Finally, the discovered movement mechanisms are systematised and evaluated in tabular form. Based on traditional solar protection typologies such as shutters, venetian blinds and pleated blinds, the aim is to identify movement possibilities on both the macro and meso levels which, due to the use of specially-made spacer textiles, offer new options for light control and visual references in the solar protection area, while at the same time making use of the natural insulating properties of spacer textiles.

Within the framework of the project, the term macro level is used to refer to the movement of the entire textile solar protection element in front of the facade opening. The textile structure itself is defined as the meso level, with the textile geometry in particular being examined. The aim is to identify further specific movement options within the textile structure without moving the entire element, in order to achieve possibilities for changes in translucency in the surface up to opacity.

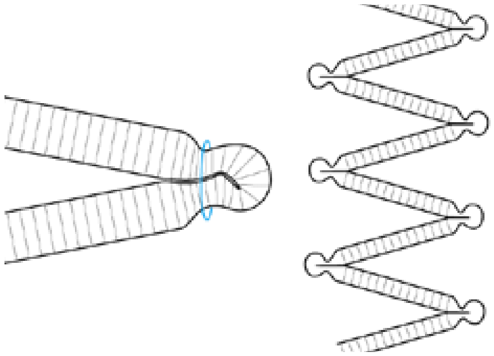


FIG. 5 Directional folding structure by stitching

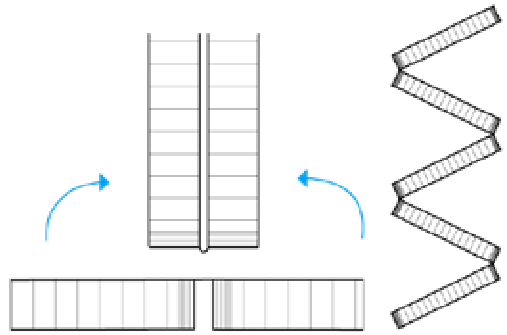


FIG. 6 Directional folding structure by incision

FIG. 7 Solar shading element, made of folded spacer textile

3 EXPERIMENTS

3.1 FOLDING AND CUTTING

Multi-layer spacer fabrics can already be produced on a laboratory scale and industrially in such a way, that they have different thicknesses due to the varying spacing of the textile layers. Stiff or thick and moveable or thin areas can be arranged alternately accordingly (Fig. 4). In this way undirected folding areas are created, which function equally as mountain and valley folds but which are correspondingly unstable in use. The textiles can thus be folded together collectively (macro level), while a defined basic transparency can additionally be set on the meso level via textile cover layers of varying density. Directional, more stable folding structures, comparable to pleated blinds, can alternatively be achieved by subsequent finishing (Fig. 5) or by alternating partial incisions in the spacer textile while maintaining the top layer opposite the incision (Fig. 6).

Fig. 7 shows a corresponding demonstrator on a 1:1 scale. Hingeless joints are achieved with the partial incisions, and transparent areas for inward and outward views are also generated with continuous incisions in the textile structure. New pleated structures are created, which can also be used as external solar protection (protected system). To this end, the stability of the textile is increased by coating or partial fillings. Robust elements can be achieved in particular by foaming in the area of the edges (see research on "3dTEX – Textile light wall element"). Further applications are currently being developed for window shutters, lift-up shutters and folding shutters as well as pleated blinds in other geometries.

3.2 BENDING, COMPRESSING AND STRETCHING

Naturally, fabrics are subject to "soft wrinkling", and therefore the subject of bending and bending mechanisms is another focus of the investigations. The elements realised so far appear accordingly to be much more "material"-like and softer than the folding structures. On the meso level, bending of the spacer textiles results in the texture of the inner surface layer being automatically compressed or condensed. The bending movement can so be used to selectively adjust areas with lower translucency (Fig. 8). Consequently, on the macro level, this means that the entire element must be correspondingly larger than the opening element. At the same time, the elements made of spacer textiles can be moved completely out of the opening area by increased bending and additional compression. As a whole, they resemble a thick, translucent curtain. Through targeted vertical stabilisation within the surface layers, the elements can also be mounted externally, comparable to the above-mentioned folding systems.

FIG. 8 Spacer textile, bending by shirring

FIG. 9 Spacer textile with partially elastic regions

FIG. 10 Spacer textile, offset cut and stretched

FIG. 11 Spacer textile, selectively stretched

FIG. 12 Spacer textile, cover surfaces stretchable in opposite directions

Moreover, warp-knitted spacer fabrics due to their mesh structure as well as woven spacer fabrics with elastic fibre components can be stretched. Like when the textiles are bent, the stretching movement changes the translucency. This can be influenced by tensioning on the entire textile structure in the surface axis, whereby the textile structure stretches and becomes more translucent (Fig. 9). Alternatively, it is possible to prepare the spacer textile by making offset incisions in the cover surfaces, so that stretching and transparency result from the pulling. The cover surfaces are then only held together by pile threads (Fig. 10). The elongation of individual, pile-thread-free textile areas perpendicular to the cover surfaces was also investigated (Fig. 11) and the elongation of individual, linear, opposite cover surface zones by bulging. Here, gill-like opening zones with an organic appearance are created that allow outward views (Fig. 12). All the mechanisms are protected.

3.3 MOVING AND FILLING

Stretchability or elasticity, compression or squeezing, just like folding, bending and rolling, are classic ways of transforming spacer textiles. The programmable geometry of the special textiles is decisive for the functionality of all these mechanisms:

The top layers of woven and knitted spacer textiles are kept at a distance from each other by so-called pile yarns. The number and position of the pile yarns as well as the density of the surfaces and the pile yarns can be defined. If only the meso level of this textile structure is considered, the most obvious and simplest movement option is the displacement of cover layers of different densities to each other (Fig. 13). This counter-rotating movement in the x- or y-axis of the textile allows light incidence and transparency to be controlled. This concept, too, is protected and will be further developed industrially. As a further option, the filling of the textile structure with magnetic colour particles is being investigated (Fig. 14). By incorporating electrically activatable magnetic metal fibres in the opposite cover layers, the position of the colour particles can be controlled, i.e. either the side facing towards or away from the building. The aim is to achieve a targeted reflection or absorption of sunlight depending on the season. At the same time, the research project is investigating filler material for densifying the three-dimensional textile structure with the aim of adaptively controlling shading and viewing at specific points and depending on sunlight incidence (Fig. 15).

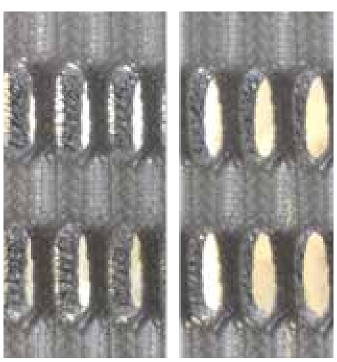


FIG. 13 Displacement of the cover surfaces of a spacer textile with respect to each other

FIG. 14 Spacer textile with side-based magnetically activatable colour particles

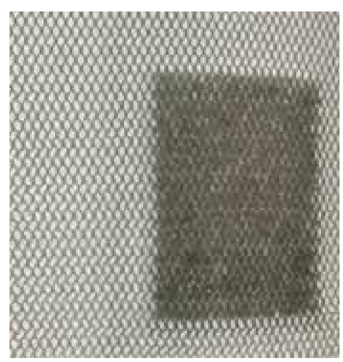


FIG. 15 Spacer textile filled with adaptive foam particles

4 RESULTS

Classical textiles are non-rigid, flexible semi-finished products whose basic moveability permits surface-related movements and size changes by, for example, controlled folding or unfolding, bending, shirring, crimping or stretching. At the same time their stability can be increased e.g. by folding or impregnating. These possibilities can be further enhanced by the use of three-dimensional textiles. Both the special movement options and the individual stiffening options of three-dimensional textiles allow the development of geometrically complex and high-quality design, stable, lightweight, translucent and opaque components as well as transparent components in certain areas. They offer passive solar energy gains in the opening area of buildings, such as protection against overheating and increased overall user comfort. In the 4dTEX project, the experimentally achieved results were processed and compared in tabular form in order to enable the comparison and evaluation of the results obtained with regard to the geometry of the textiles.

4.1 FLAT SOLAR PROTECTION ELEMENTS/ SHUTTERS

Fig. 16 show flat solar protection elements based on classic shutters such as folding, sliding, window, lifting and roller shutters. In lines 1 and 2, category A, these mechanisms are first categorised on the macro level. In columns 5, in particular, initial mechanisms can be recognised which can only be realised with textiles, and in particular with stretchable textiles. Category B, line 2, shows on the meso level the possibilities that exist beyond this and through use of the special geometry of three-dimensional textiles. This is where the experimentally achieved results come in. In addition, further options or possible variations of these results appear, as shown in particular in columns 2, 4 and 5. Categories C and D show additional findings on how the thermal properties of spacer textiles can be improved and how other active and passive uses of solar energy can function. Results such as foaming with flexible foams or alternatively the use of strongly crimped fibres for insulation are currently being used for the preparation of further research projects, as are the use of light-conducting fibres and the question concerning the use of volume-adaptive foams. Findings are also being used for the development of unfoamed spacer textiles with elastic pile yarns (also called FGL yarns) for controlling the element thickness (column 4) as well as for unfoamed spacer textiles with electromagnetically-controlled PCM-based colour pigments (column 5). Category E additionally shows potential filter functions (pollen filter, fog filter/water trap) as well as the sound-absorbing possibilities of the textile elements.

Finally, one of the experimentally and tabularly elaborated options of a flat element was examined in terms of its design. A pneumatically or adaptively controlled stretching mechanism perpendicular to the textile surface was selected. It is used for the selective control of incident daylight and the simultaneous increase of transparency in areas that are not shaded. Fig. 17 shows a corresponding facade simulation.

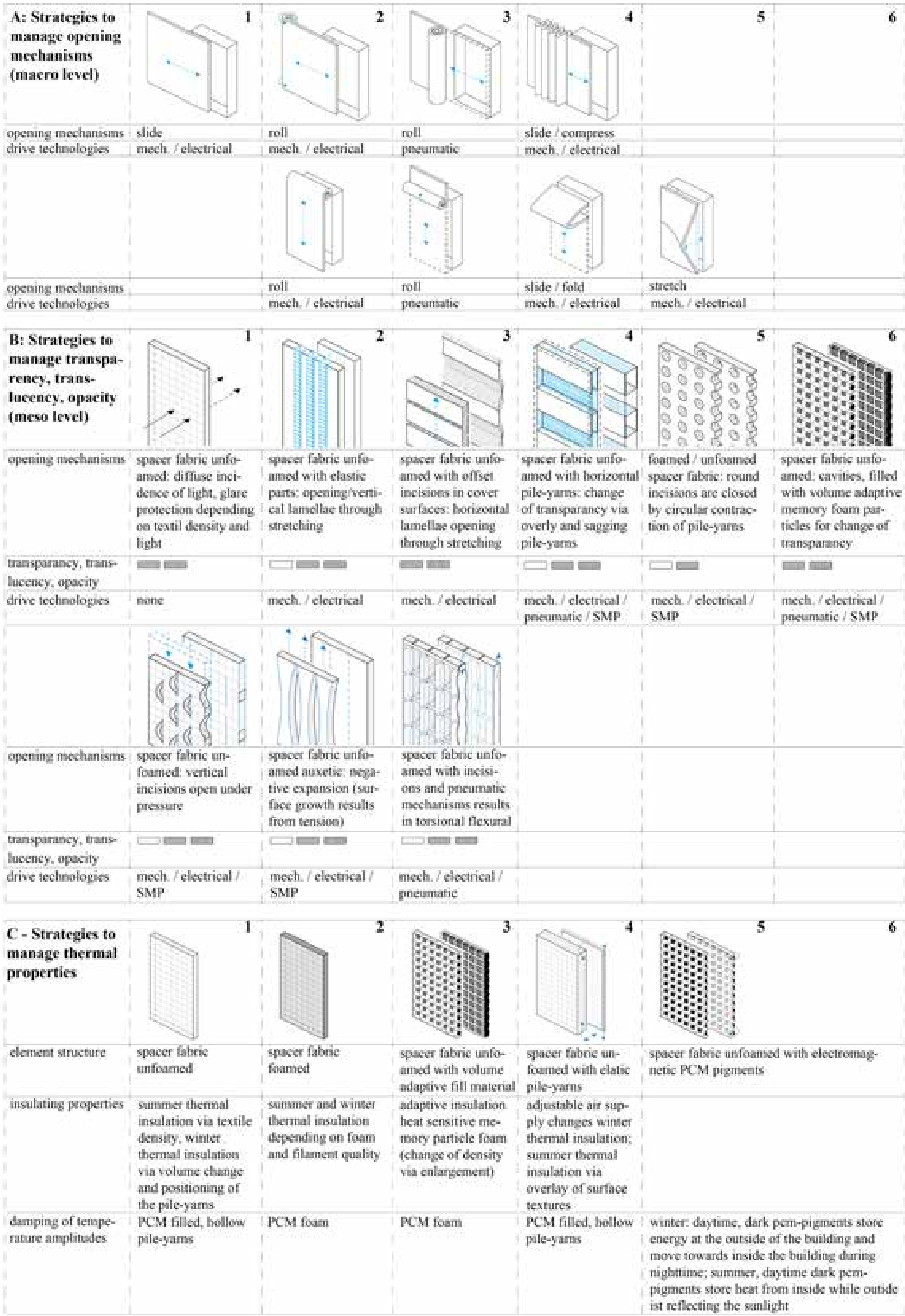
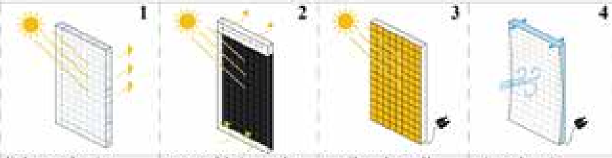


FIG. 16 .1 Shutters: A, B, C



D - Strategies to manage passive and active use of solar energy	1	2	3	4	5	6
mechanism	light-conducting fibers	spacer fabric used as solar collector	textile solar cells	piezoelectric		
light guidance	daylight management via light-conducting fibers					
power or heat generation		heat generation along the fur structure of icebears	power generation along the research on semiconductor and coating technologies	power generation via micro movenments initiated by wind suction / pressure		

E - Others: Strategies to manage air filtration, sound insulation, water extraction	1	2	3	4	5	6
mechanism	spacer fabric unfoamed, open pored	spacer fabric unfoamed, open pored	spacer fabric unfoamed, open pored			
functionality	filter for fine dust, pollen, insects	sound insulation depending on density, weave or knitting structure	textile fog collector			

transparent
transluzent
opak
SMP Shape Memory Polymer

FIG. 16 .2 Shutters: D, E

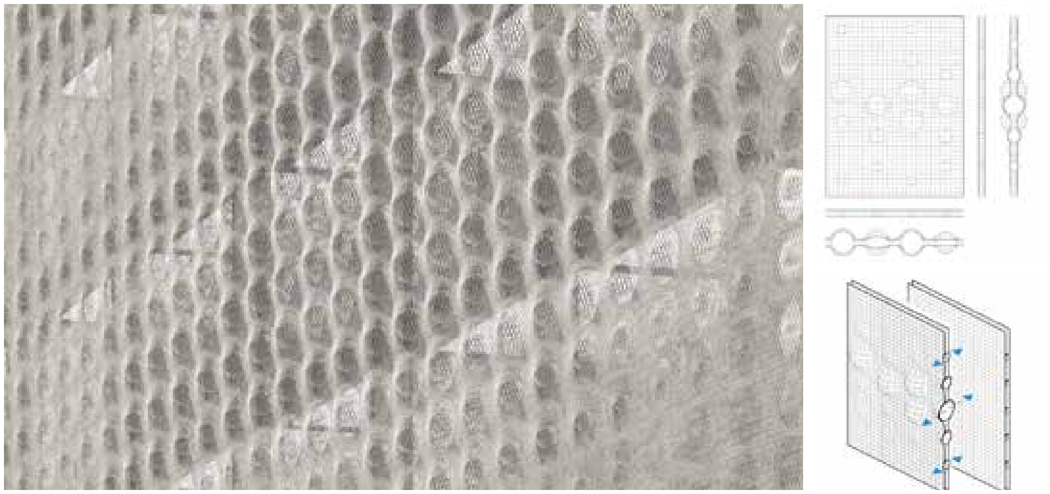
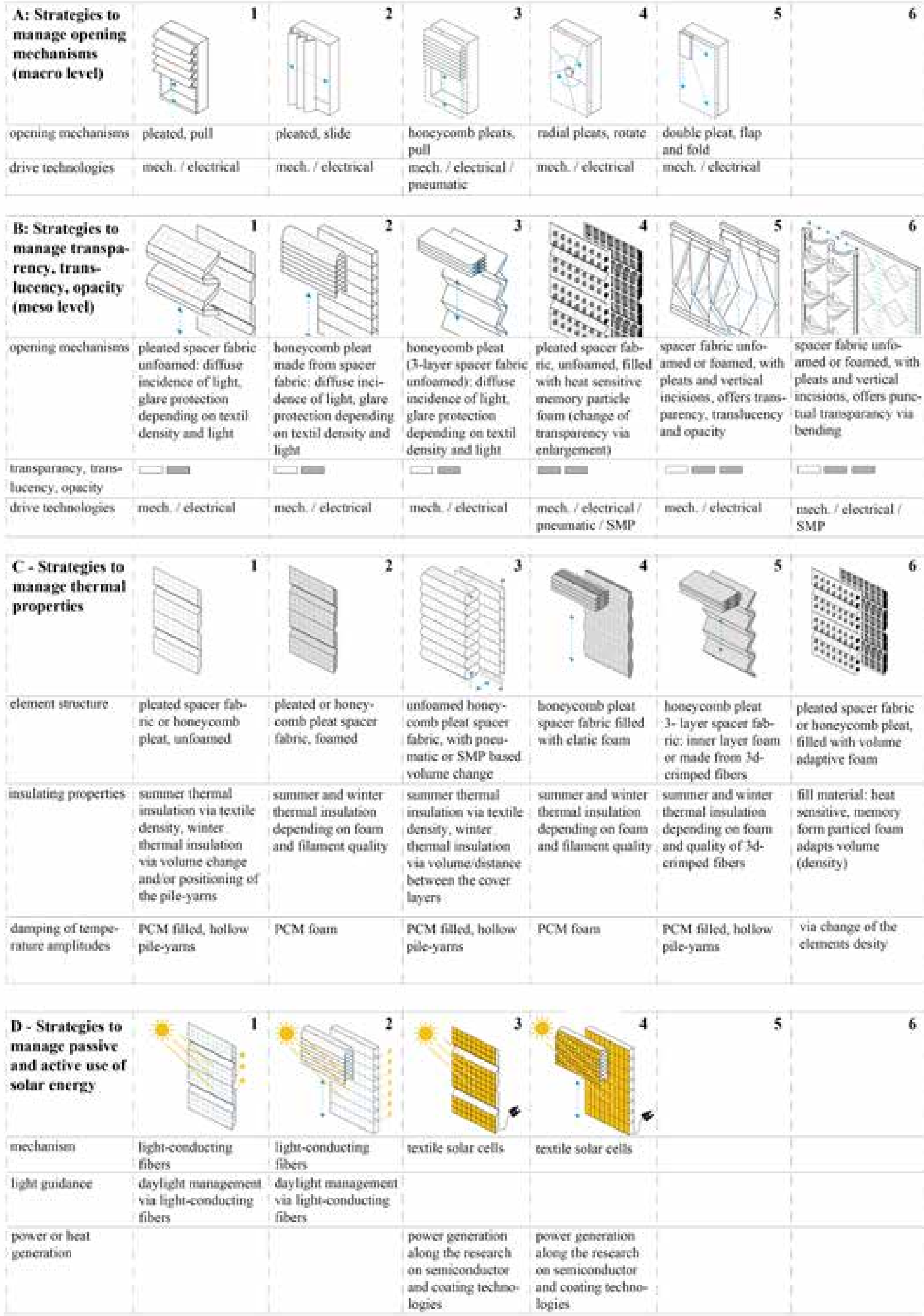


FIG. 17 Spacer textile, selectively stretched and in line with sunlight

FIG. 18 Folded and cut spacer textile for exterior sun protection

4.2 FOLDED, CURVED SOLAR PROTECTION ELEMENTS (PLEATED BLINDS)

Fig. 19 shows in lines 1 and 2 of category A (macro level) folded solar protection elements, i.e. pleated blinds including honeycomb pleated blinds. Here again, in columns 4 and 5 (Miura folding) in particular, initial mechanisms can be recognised, which can be realised above all with 3d textiles and in particular partially elastic textiles. Category B, line 2 shows on the meso level which other possibilities arise through the use of the special geometry of three-dimensional textiles. This is where the experimentally achieved results come in. In addition, further options or possible variations of these results appear, as can be seen in columns 2 and 6 in particular. The latter shows the development of a thermally optimised, three-layer pleated or honeycomb pleated blind.



A: Strategies to manage opening mechanisms (macro level)	1	2	3	4	5	6
opening mechanisms	pleated, pull	pleated, slide	honeycomb pleats, pull	radial pleats, rotate	double pleat, flap and fold	
drive technologies	mech. / electrical	mech. / electrical	mech. / electrical / pneumatic	mech. / electrical	mech. / electrical	

B: Strategies to manage transparency, translucency, opacity (meso level)	1	2	3	4	5	6
opening mechanisms	pleated spacer fabric unfoamed: diffuse incidence of light, glare protection depending on textil density and light	honeycomb pleat made from spacer fabric: diffuse incidence of light, glare protection depending on textil density and light	honeycomb pleat (3-layer spacer fabric unfoamed): diffuse incidence of light, glare protection depending on textil density and light	pleated spacer fabric, unfoamed, filled with heat sensitive memory particle foam (change of transparency via enlargement)	spacer fabric unfoamed or foamed, with pleats and vertical incisions, offers transparency, translucency and opacity	spacer fabric unfoamed or foamed, with pleats and vertical incisions, offers punctual transparency via bending
transparancy, translucency, opacity						
drive technologies	mech. / electrical	mech. / electrical	mech. / electrical	mech. / electrical / pneumatic / SMP	mech. / electrical	mech. / electrical / SMP

C - Strategies to manage thermal properties	1	2	3	4	5	6
element structure	pleated spacer fabric or honeycomb pleat, unfoamed	pleated or honeycomb pleat spacer fabric, foamed	unfoamed honeycomb pleat spacer fabric, with pneumatic or SMP based volume change	honeycomb pleat spacer fabric filled with elatic foam	honeycomb pleat 3- layer spacer fabric: inner layer foam or made from 3d-crimped fibers	pleated spacer fabric or honeycomb pleat, filled with volume adaptive foam
insulating properties	summer thermal insulation via textile density, winter thermal insulation via volume change and/or positioning of the pile-yarns	summer and winter thermal insulation depending on foam and filament quality	summer thermal insulation via textile density, winter thermal insulation via volume/distance between the cover layers	summer and winter thermal insulation depending on foam and filament quality	summer and winter thermal insulation depending on foam and quality of 3d-crimped fibers	fill material: heat sensitive, memory form particel foam adapts volume (density)
damping of temperature amplitudes	PCM filled, hollow pile-yarns	PCM foam	PCM filled, hollow pile-yarns	PCM foam	PCM filled, hollow pile-yarns	via change of the elements desity

D - Strategies to manage passive and active use of solar energy	1	2	3	4	5	6
mechanism	light-conducting fibers	light-conducting fibers	textile solar cells	textile solar cells		
light guidance	daylight management via light-conducting fibers	daylight management via light-conducting fibers				
power or heat generation			power generation along the research on semiconductor and coating technologies	power generation along the research on semiconductor and coating technologies		

FIG. 19 Folded Blinds

FIG. 20 Bend and compressed spacer textile for external solar protection

Categories C and D show, as already with the flat elements, additional results. Thermal properties and other active and passive uses of solar energy can also be implemented in the folded textile elements due to the three-dimensionality of the textiles. In particular, columns 4 and 5 of category C, which represent geometric variations of honeycomb pleated blinds manufactured as spacer textiles, show how the thermal properties have been further developed as regards insulation. Category E shows the same options as already described for the shutters.

Finally, one of the experimentally and tabularly elaborated options of a folded element was examined in terms of its design. A folded and cut surface with comparable functions to the flat element in Fig. 17 was selected: Selective control of incident daylight with simultaneous increase of the transparency in areas that are not shaded. Fig. 18 shows a corresponding facade simulation.

4.3 MIXED TYPOLOGIES

In the 4dTEX project, venetian blinds were also investigated as a third typology. Here there were no geometrically-induced new solar protection elements made of spacer textiles. The main result was that three-dimensional textile production could enable the manufacture of venetian blinds in a single industrial step. Whether this makes commercial sense was not further evaluated.

For 4dTEX, exciting results have emerged in the field of mixed typologies. Should bending (Fig. 20) already be a special case of folding, the elements shown in Fig. 9 can be described as "Stretch_Bend_Venetian_Roller". And the element depicted in Fig. 21 also represents a typological special solution. Based on the torsional flexural buckling mechanism realised at the University of Stuttgart under the name "FlectoFold", a torsional flexural fold is triggered by bending the spacer textile. The bending has already been investigated in advance with respect to design and in the form of a facade simulation (Fig. 8). In combination with the FlectoFold mechanism, this could for the first time not be generated additively in individual elements but from a surface which, in addition to the bending, also allows areas with partial openings for viewing.

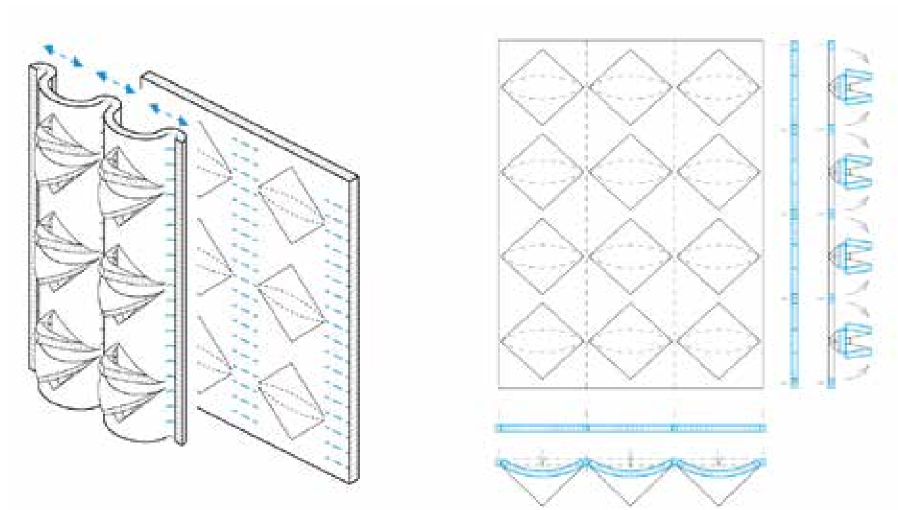


FIG. 21 Torsional flexural buckling in the surface

5 CONCLUSIONS

In summary, the theory can be confirmed that, with the help of three-dimensional textile technologies, new design and functional options for moveable, solar shading and insulation elements can be created. The results make the enormous potential of spacer textiles in the solar protection area – especially on the meso level (all the systems are now protected) – abundantly clear. The research project also shows that the conception of these complex three-dimensional structures can be effectively represented in the first step using drawings and sketches as well as with adapted, marketable spacer textiles. At the same time, the production of textile samples is very time-consuming, and therefore the next project proposal will include the question of how on the one hand the digital simulation of these textile structures can be improved, and how on the other the interface of this simulation software to the software used on the textile machines can be designed in the future. The aim is to better synchronise architectural and structural concerns with the manufacturing techniques and possibilities of textile production.

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Automated digital workflows for façade detailing and manufacturing

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Abstract

Building Information Modelling (BIM) has become the leading digital process in early stage development of larger construction projects. However, BIM Models at tender stage, usually have a comparatively low Level of Detail (LOD) which does not provide sufficient information for CAM production. The manufacturers therefore need to further develop the model to meet the requirements for production.

The current standard process for the development of complex façade systems is split into two parts. Defining the principal detail and creating tailored 3D Models as a basis for digital manufacturing. The second part however is currently a quite labour-intensive process and requires highly trained staff. The 3D modelers are now the production content creators. Through the increased usage of CNC production technology, they have become the processes bottle neck, especially when dealing with complex façade systems.

An algorithm-based workflow was developed to create 3D Models at manufacturing level from low level design model. Instead of the labour-intensive modelling approach, this workflow automatically created highly detailed models for manufacturing through custom developed algorithms.

This workflow was successfully implemented by the construction design team for the creation of the Closed Cavity Façade (CCF) Elements of the "crown" of Fenchurch Avenue 10 Highrise in London, by Eric Parry Architects.

Aside from process and cost advantages in comparison to the traditional workflow, this process leaves room to also integrate modelling techniques, that are not feasible for manual modelling. Topology optimized or multi-functional façade knots for example can be generated and used as input for 3D printed building parts.

Modelling automatization for the creation of highly detailed models will influence the digital workflows in façade manufacturing significantly. It will build the basis for the integration of emerging technologies, such as the 3D printing of building parts in the façade industry.

Keywords

BIM, Digital Workflow, Façade Design, File to Factory, Programming Approach

1 INTRODUCTION

Building Information Modeling (BIM) has become the standard process in medium to large scale building design. BIM is an emerging technological and procedural shift within the Architecture, Engineering and Construction (AEC) industry (Succar et al., 2007). When implemented correctly, all involved parties benefit greatly from BIM processes. Mainly through the following key aspects: Early detection of design inconsistencies and simplified coordination throughout all involved parties (Czmoch and Pekala, 2014).

2 DIFFERENCES IN BIM MODEL REQUIREMENTS OF DESIGNERS AND MANUFACTURERS

At tender stage, the BIM models of architects and engineers usually do not meet the criteria for an unaltered direct usage by façade manufactures. This should not be mistaken for lack of quality of these models. It is merely a result of the intended purpose of these models. Models from the architects are optimized for quick adaptability and aimed to define the overall design intend and therefore need to leave room for different detail solutions, which might be offered by different competing façade manufacturers. Therefore, the level of detail therefore is low.

Façade manufacturers have very different requirements for their models. The key difference is the requirement for a very high level of detail to ensure the suitability throughout their complete internal workflow processes. On the one hand, these models are intended to ensure buildability and functionality. On the other hand, they need to provide and store all information necessary for the production, material purchasing, assembly and installation of the developed construction. They essentially need to be fully featured models to meet these requirements, but mainly to be able to provide valid input for computer aided manufacturing (CAM).

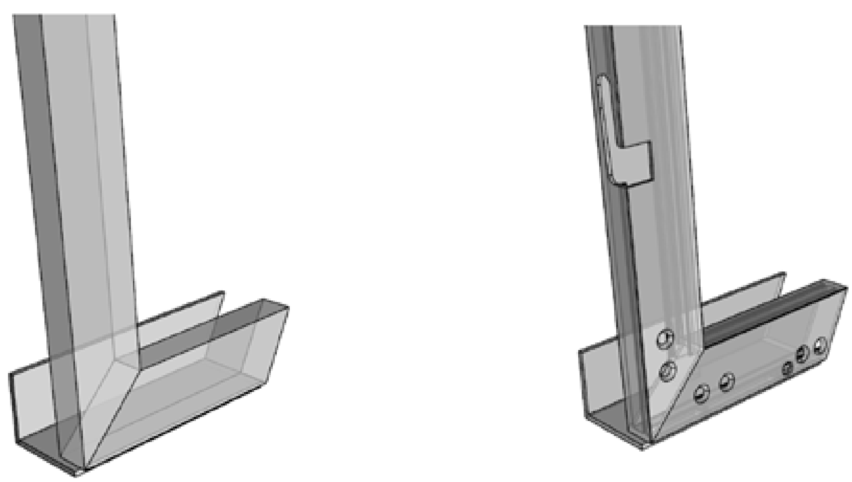

FIG. 1 Images of the same structural glazing carrier frame as visual example of differences in the level of detail of an architects' model (left) and manufacturer's model (right).

3 CURRENT PROCESS OF CONTENT CREATION AND REFINEMENT

The digital content gap resulting from the different BIM model requirements need to be filled by the façade manufacturers through integration of their expert knowledge. They need to refine the CAD 3D model to fit their needs while adding all relevant property information.

In context of high-end façade design, currently one of the most common 3D based workflows for the content creation and refinement is organized in these basic sub-processes:

- Design development and 2D detailing
- 3D modelling of the detailed construction
- Preparatory work for the production and assembly

In the design development and detailing process, the intended façade design is developed by the manufacturer to meet the functional and visual requirements of the façade. In the first iteration this process is usually still 2D drawing oriented, since the process is usually subject of many radical changes in the early design stages. Once a certain level of clarity of the intended construction is reached, a digital mock-up is created to ensure the construction principle is also fully valid in 3D space. In some cases, even a physical mock-up is built.

Once the lead detailing is finalized and approved by the client, it is applied to the complete façade to create the digital basis for the downstream processes. Emerging deviations from the details and special cases, not covered by the lead detail are solved during this process as well. For projects with low repetition factors, this project phase is very labor intensive.

Once the 3D basis of the building has been finalized, the model and the information held within is used as a basis for the work preparation. This includes many subprocesses such as the creation of assembly drawings, CNC-data extraction and data integration into the enterprise-resource-planning (ERP) software. These models will also be used as the basis for the BIM coordination models.

4 THE CHANGED ROLE OF THE 3D MODELER

For many projects the use of BIM can be as basic as the availability of a 3D model produced by one or more of the specialty contractors (3). Since 3D modelling is a key requirement for actively participating in BIM processes, many processes that used to be based on 2D plans now rely on 3D data.

This has changed the role and increased the importance of 3D modelers. In the 2D process, the tools and process available to the team contribute to a distinct inability to see, think and document in an integrated 3D way (Ernstrom et al., 2015).

In order to perform their job correctly, they need to actively transform construction principles presented in 2D into a 3D geometry, while developing construction solutions of the areas not shown in the lead detailing. They also need to incorporate the knowledge of the production processes to select the correct method of modeling and thereby ensure the design model is suitable for the CNC production.

They are required to work very accurately, since their output in the 3Dmodel is directly transferred to the CNC machine. Any mistake directly leads to cost-intensive manufacturing errors.

The creation of highly detailed models is relatively time-consuming in comparison to the creation of 2D drawings. The benefit is gained usage of the model throughout the complete digital process such as: early error detection, possibility to derive part and assembly drawings, possibility to derive CNC production data, BIM participation through coordination models and intelligent bill of materials (BOM) generation.

5 INCREASED RISK OF HUMAN ERRORS

The changed role and importance of the 3Dmodeler result in an increased workload for the 3D modeler. In combination with timely pressure caused for example by tight deadlines, the risk of human errors increases. This is especially true for complex façade constructions, where the amount of unique parts and construction principles is comparatively high and the repetition factor is low (Bailey et al., 2005). Through the high level of detail, even small changes in late stages of the design, can result in large amount of adaption work, which further increases the workload and therefore also the risk of human error.

Workload distribution would be a suitable countermeasure. However, this is difficult to implement in practice. The requirements to the knowledge and skills of the 3D modelers are relatively high and usually not met by a many team member. The same is true for hiring additional staff. Experienced and skilled personnel is hard to find on the open market. Graduates usually do not meet the key requirements on the construction knowledge side. Additional training is one possibility but on the other hand time and resource intensive.

6 CONTENT CREATION AND REFINEMENT VIA PROGRAMMING

The adoption of BIM in building design and construction planning appears to provide competitive advantage, technological opportunity and ability to address structural and process problems that exist (Dossick and Neft, 2010) (Love et al., 2011). One of the main reasons why BIM processes are based on 3D models instead of 2D drawings is their different level of interpretability by a computer. To derive a complete 3D geometry of an object from a 2D drawing, several drawings have to be considered simultaneously. Also, all drawings leave room for interpretation, which is normally filled by the trained workers knowledge. Due to the difficulty to match information from different drawings, buts mainly through the lack of information, it is close to impossible for computers to automatically generate a flawless 3D model based on 2D drawings.

In manufacturing, main target of the digitalization was the automation of its key aspects, the production. The introduction of CNC technology has increased the productivity and accuracy of manufacturing extremely. But it also increased the requirement for the input data at the same time. In contrast to the former drawing-based approach, the data may not leave any room for interpretation.

All digital content information is potentially creatable through a computer algorithm. This is also true for the work done by 3D modelers. Nevertheless, certain aspects of their work require a much greater effort to automate than others.

In facade design, the development of the construction principles is the very hard to automate and will probably require the human intellect for quite some time.

Once rules and construction dependencies are clear, these principles can be turned into custom developed algorithms, which apply these rule sets and generate information enriched 3D models as a data resource for downstream processes. This approach has many advantages, such as

- the work load of the 3D modelers is reduced significantly, while assuring a steady model quality.
- changes in late stages of the design phase can be integrated more easily through keeping the late point of finalization.
- it is also possible to integrate additional processes that are beyond the usual 3D modelers scope of work, such as ERP integration.

7 CASE STUDY OF APPLICATION FOR CONTENT CREATION ALGORITHMS (PROGRAMMING APPROACH)

7.1 PROJECT DESCRIPTION

The programming approach was used for the realization of the "Fenchurch Avenue 10" building in downtown London. The "crown" of this new iconic building, designed by Eric Parry Architects, with size of approx. 5.000 m^2 was to be realized as a Closed-Cavity-Façade (CCF) by Josef Gartner GmbH (Gartner). Imagine computation was involved as their subcontractor for the 3D content creation of all manufacturing parts.

Event though, the design of the building is not what is commonly referred to as complex geometry within the design community, the complexity at the manufacturing level is relatively high and results in a very high number of individual components and unique prefabricated façade elements. Out of the 1058 elements 87% elements were uniquely shaped. Each Element contained of approx. 150 individual parts and 300 fasteners to individually place.

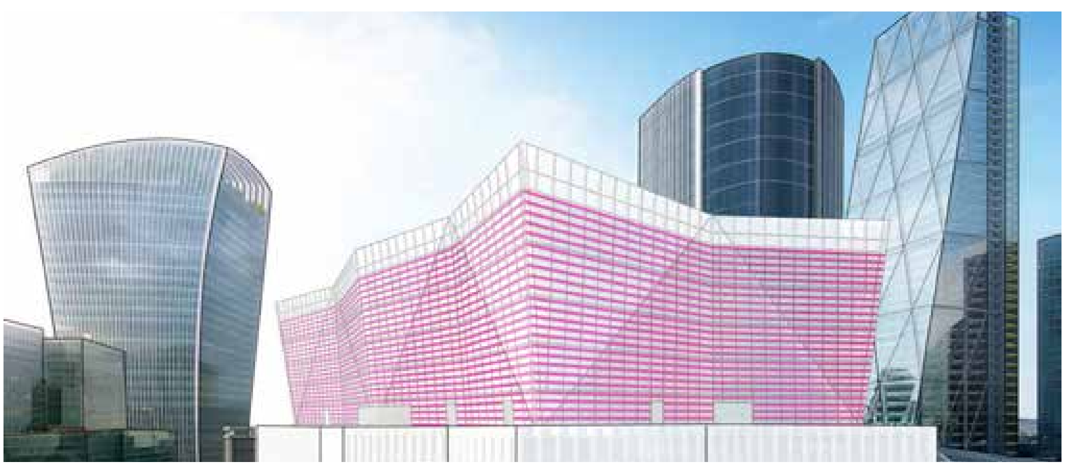

FIG. 2 Schematic Rendering of the Fenchurch Avenue 10 "crown" façade in London designed by Eric Parry Architects.

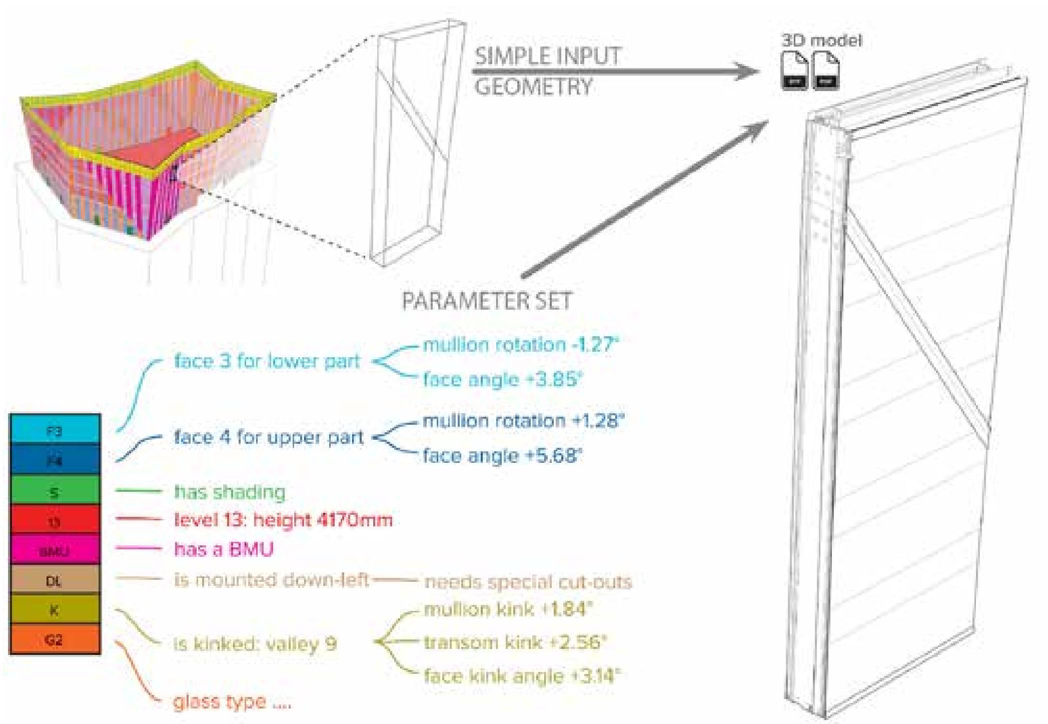

FIG. 3 Schematic visualization of the geometric input and the driving parameters of the algorithm which leads to the final highly detailed model.

7.2 ORGANIZING THE FAÇADE ELEMENTS' COMPLEXITY

To organize the individual configurations of the façade elements, each element was assigned a set of parameters assigning them their functional requirement. There were 43 driving parameters which were categorized into the following seven clusters: face- and mullion type, shading system, location, maintenance unit, geometric requirements, functional requirements and mounting direction. This lead to approx. 31.500 possible variations of which 760 variations actually occurred in the project.

7.3 AUTOMATION

A combination of simplified geometric grid, the driving parameters (Tab. 1) and a standard part library, containing mainly fasteners such as screws, were the input to the custom developed algorithm. Based on the given input set the construction logic was individually determined. Depending on the parameters, the algorithm independently chose which base parts were necessary to create, where to place them, how to cut them, how to connect them, how to name them, which construction tolerances to keep and which coating to apply to them. The algorithm was developed as a .NET Plug-In for Rhinoceros using the Microsoft .Net Framework. Data was delivered to the façade Manufacturer in 3DM, STEP, IGES, SAT and 3DPDF format. BOM Data was transferred in a special XML base Data format which could be integrated through an existing interface of the manufactures ERP System (SAP).

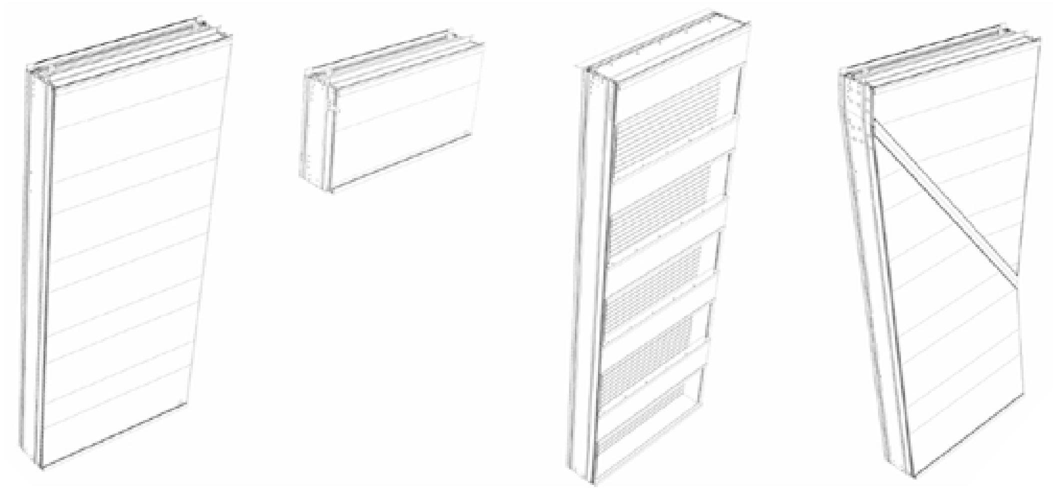

FIG. 4 CAD Models different façade element types created by the same algorithm but different parameter sets.F.l.t.r.: Standard Element, "Above Door" Element, Louver Element, Kinked Element Size of Standard Element: ~4m x 1.5 m

Within two to four minutes of calculation time on a common Windows CAD workstation, a model containing around 150 individual components and 300 screws was generated. A process that would have taken up to 4-5 days per element in a classic modelling approach.

The output of the algorithm had to meet the same high standards as data which was created through classic modelling. To ensure the quality of the model several additional methods were programmed to check the integrity of the model as a post process.

One key difference of the programming approach in comparison to parametric modeling, is that parametric modelers can only create different geometric variations based on the same creation rules. As long as the model stays within the same creation logic, it can adapt to changes of the parameters easily. In this project however, the defining rules of the elements changed – something a parametric modeler cannot handle within one model. This means - if these elements had to be created through a parametric model, almost all of them had to be modelled as individual parametric models.

7.4 TIME LINE COMPARISON

The calculation time alone however cannot be directly compared to the modelling time, since the creation of the code development in order to generate the model also takes a significant amount of programming time. In retrospective, the programming approach as it was applied to this project, has been significantly faster than the classic modeling approach would have been. Main reasons for this assessment are the comparatively low element repetition ratio and a large number of different, but similar defining rule sets.

A general assessment on which approach will take less time to implement cannot be made, since the parameters influencing the required modeling time and the required programming time differ. Each project as to be examined individually. The most influential parameters in favor of the programming approach are: low repetition of parts and a large project size.

DRIVING PARAMETER	TYPE	DRIVING PARAMETER	TYPE
SimplifiedGeometricFrame	CAD Input	SunShadeMotorType	Enum[int]
ElementType	Enum[int]	SunShadeMotorLocation	Enum[int]
TopFaceAngle	double	HasBuildingMaintainanceUnit	bool
BottomFaceAngle	double	IsGroundFloorConnected	bool
TransomProfilesTopLeft	CAD Input	InnerGlassType	string
TransomProfilesTopRight	CAD Input	OuterGlassType	string
TransomProfilesBottomLeft	CAD Input	IsGlassReplaced	bool
TransomProfilesBottomRight	CAD Input	Mounting Direction	Enum[int]
MullionProfilesRightTop	CAD Input	BracketType	Enum[int]
MullionProfilesRightBottom	CAD Input	Gasket-Type	Enum[int]
MullionProfilesLeftTop	CAD Input	LouverSpacing	Double
MullionProfilesLeftBottom	CAD Input	HasDoorCladdingRight	bool
IntermediateBeamProfileLeft	CAD Input	HasDoorCladdingLeft	bool
IntermediateBeamProfileRight	CAD Input	HasDoorCladdingBottom	bool
TransomProfileLeft	CAD Input	IsCutOutAtCladding	bool
HasHiddenBeamReinforcement	Bool	IsCornerCNCMilledTopRight	bool
HiddenBeamReinforcementProfile	CAD Input	IsCornerCNCMilledTopLeft	bool
KinkDirection	Enum[int]	IsCornerCNCMilledBottomRight	bool
MullionRotationAngleLeft	Double	IsCornerCNCMilledBottomLeft	bool
MullionRotationAngleRight	Double	MountingbracketTypeLeft	Enum[int]
HasShading	bool	MountingbracketTypeLeft	Enum[int]
SunShadeType	Enum[int]		

TABLE 2 Overview of the driving parameters

7.5 INTEGRATION OF COST OPTIMIZATION

Programming the construction logic allows to integrate optimization procedures. Other than in classic parametric modeling approaches, the selection of construction rules can be changed not only by the input parameters, but also by algorithm-based reevaluating of the generated result.

In this case study, this was used while handling the glass geometry. Since the majority of the façade elements were non-rectangular but nearly rectangular, the glass panels were by rule individually shaped. However, if the geometry results were within a small tolerance to a perfect rectangle of up to 4mm at top and bottom, this shape was used instead to reduce complexity of the part. The change in geometry was then compensated by individual glass supports, which also were changed accordingly by the algorithm.

Optimization algorithm were also use in the context of the kinked elements, in which movable blinds needed to be installed. Moveable blinds need to run within one plane, which, depending on the location of the kink within the panel, could resulted in clashes with the intermediate transoms of the element. Therefore, the optimal plane for the blind placement was determined by an optimization algorithm, choosing the plane with least deviation from the intend location while assuring clash free operation of the blind. The algorithm tested several blind plane tilting options based on the give entry point of the blinds motor. A volume representing the blinds and the necessary minimum distances was tilted in two degrees of freedom with the goal to find the plane, with the smallest deviation from the originally intended plane (Fig. 5).

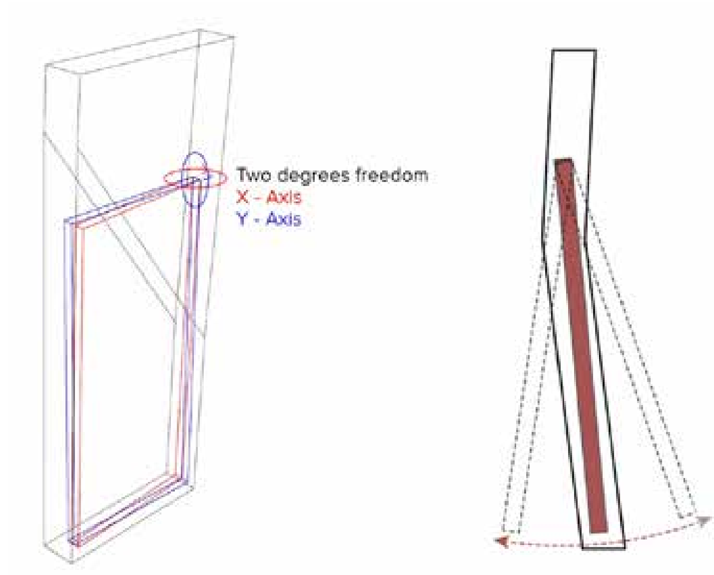

FIG. 5 Visualisation of the movable blind plane detection algorithm. Perspective and Side view of the same element showing a volume representing the blind tolerances. The algorithm tests several tilting angles to let the blind run clash free within the sealed premanufactrued façade element.

7.6 COMBINATION OF APPROACHES

Some special geometric cases are very time consuming to integrate into an algorithm up until to the point, where the amount of time needed to integrate them is significantly higher, than to solve the special case by the classic modelling approach. A geometric special case in this context defines an Element within the building, of which the construction logic significantly differs from the majority of the other elements. In this project the four bottom corner elements were defined as special cases, since they are the only elements, which need to handle four different face angles which results in many additional technical requirements and special details. In these cases, it is beneficial, that the output models of the programming approach are static – not parametric models. This allows to easily adapt geometry without corrupting parametric interdependencies. Usually, 3D models which are generated as a basis for later adaption, are generated through code and then altered my 3D modelers to fit the special geometric requirements.

8 INFLUENCE ON THE OVERALL PROCESS.

8.1 QUALITY ASSURANCE - CONSTANT QUALITY

The algorithm-based programming approach, has the benefit of constant quality, since the model quality is directly related to the quality of the custom developed code. Therefore, it is constant throughout everything that was generated based on the algorithm. If one code generated element is completely correct, all instances will be correct. If there is a mistake resulting from an algorithmic error, it will be found in every instance. This means that random quality checks of the 3Dmodel are more meaningful in regards of the quality of the complete series of generated elements. Also, their occurrence is more likely to be detected and corrected early in the process.

This is a major difference to the quality of 3D models created through direct modeling. Here the quality depends highly on the skills and knowledge of the modeler creating it. Human errors occur in non-repeating patterns and increase with the workload of the 3Dmodeler. Random checks therefore are less meaningful.

8.2 LEAD TIME OF PROGRAMMING

A major advantage of the programing approach for the overall process is the fact that a large portion of the development can be started without finalized details. Geometric dependencies need to be clear – final dimensions do not have to be finalized up until the very end of the programming cycle. This allows to start early with the programming work and reduces the time needed between approval of the lead detailing and the start of manufacturing.

8.3 EXTENDED FLEXIBILITY

The programming approach requires the programming to be finalized before presenting any final results. Once it is final, generating the output is very quick. So, adaptions to the code can be integrated much later in the process than in the classic modeling approach, since the time for the actual generation of the output is significantly shorter. Due to easy adaptions large parts of the programming work can start in half way through the design development phase. When looking at the overall process the programming is mainly an automation process that is substituting large aspects of the latter two sub-processes mentioned in section 3: "3D modelling of the detailed construction" and "Preparatory work for the production and assembly".

9 CASE STUDY - LESSONS LEARNED

It turned out that the generated final elements had an incredibly good quality. The manufacturing, element assembly and mounting of the elements went through without any errors or delays that originated from the quality of 3D model.

This was also a result of the thorough testing of the algorithms' output against consistency with lead detailing and its underlying construction principles. Theses testing cycles were necessary mainly due to the occurrence of "special cases" originating from certain parameter combinations, which were initially not covered by the developer. Also, the output revealed areas in which applying the construction logic of the given lead detailing resulted in non-functional constructions. In these cases, the lead detailing was further refined.

Quite surprising was the 40/60 percent ratio of required development time for geometry generation and generation of non-geometric information. The integration of a codification system for part identification, BIM property generation, CAM data export and data formatting for ERP integration, was a much larger part than originally anticipated.

When generating geometry, every part is usually treated as a unique part. The detection of identical parts, is a challenging and development intensive procedure. Generally, it creates the potential risk of wrongly identifying two slightly different parts to be identical. From the manufacturers point of view however, it is despite the usage of CNC technology very important to keep the amount of unique parts to a minimum and therefore detect identical parts. The in this case rather late integration of the identical part recognition algorithms turned out to be a large challenge, that could have been avoided when they had been integrated earlier in the process. Part recognition was integrated into the creation process. Not the final results were compared with a given tolerance. Parts were detected to be equal if the driving parameters of the part are identical. In summary, all the involved parties are convinced that they will again follow the programming approach when dealing with complex constructions.

10 OUTLOOK

With an increasing amount of AEC processes relying on BIM Data, information enriched 3D models will become increasingly important. New processes will require new types of Information to be associated. Ensuring the quality of the stored data and their correct association within the 3D BIM models will become of increasing importance. Automated data creation through project specific programming is one approach to face this challenge.

Aside from BIM Data generation, emerging manufacturing technology for the AEC industry such as additive manufacturing (3D Printing), will benefit greatly from the programming approach.

Through additive manufacturing the geometrical and structural complexity of joints could be dissolved trough one single 3D printed part incorporating the complexity. This leads to a shift of whom needs to deal with the complexity. The complex joint is not any longer resolved by the craftsman in the workshop, but by the 3D Modeler, creating the digital model, which later will be 3D printed. The true benefit of this shift from the analog to the digital workspace is the possible integration of digital tools. To create a topology optimized multi-functional façade knot for example, an algorithm could evaluate several data sources and generate the 3D model accordingly. Data sources in this context could be for example structural requirements or production process requirements.

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Development of a holistic performance approach for facade design

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Abstract

As a significant building sub-system, facade needs to be designed through the consideration of a wide range of factors. Facade design is given shape as a result of a collaborative work by stakeholders from different disciplines based on outdoor (environmental) and indoor (spatial) conditions, as well as project specific constraints, time/ budget limitations, legislation in order to fulfil functional, environmental and financial requirements of the project/users. Even just functionality related performance attributed to a facade is multifaceted such as structural, daylighting, or acoustic. Although, in literature there are researches focusing on different aspects of facade performance, there is a lack of a holistic point of view that considers different aspects at once. Aim of the paper is to present (a part of) a tool developed to be used during the facade design process and counts functional performance aspects altogether. The tool provides a holistic systematic approach in order to support the design optimization. It is intended to assist decision-makers while giving decisions on facade parameters (design variables) to consider their interactions with functional performance aspects in possible environmental and spatial conditions. The tool is in the form of spreadsheet designed via Microsoft Office software. The functional performance aspects included in the tool are structural, fire, water related, air permeability related, thermal, moisture related, daylighting, and acoustic performances. The facade parameters defined as the main decision subjects within the tool are orientation, transparency ratio, facade type, window type, glazing, framing, shading, wall configuration, finishing, and detailing. First, for each facade parameter, design options are generated to keep the tool relatively simple and comprehensible. Then, matrices having design options in rows and performance aspects in columns are established. To support the decision-making, each intersecting cell in matrices proposes a rating or a rating prescription having conditional guidance. So, the tool user is expected to rate each option in terms of each performance in accordance with the prescriptions. The information provided in the tool is based upon an extensive literature review. The tool is composed of separate but interconnected rating charts designed for each facade parameter (the rating chart for orientation is presented in the paper). The overall facade performance is illustrated by a spiderweb graphic which has separate sections for each performance. Briefly, the tool is believed to enable the decision-makers to trace the consequences of their design decisions holistically, to give the decisions in a transparent way by highlighting the compromises in design, and to support the communication among stakeholders.

Keywords

Facade design, facade performance, decision-making, decision support tool, holistic design

1 INTRODUCTION

As a significant building sub-system, facade needs to be designed through the consideration of a wide range of factors. Facade design is given shape as a result of a collaborative work by stakeholders from different disciplines based on outdoor (environmental) and indoor (spatial) conditions, as well as project specific constraints, time/ budget limitations, legislation in order to fulfil functional, environmental and financial requirements of the project/ users (Knaack et al., Klein, 2013). Even just functionality related performance attributed to a facade is multifaceted such as structural, daylighting, or acoustic. Although, in literature there are researches focusing on different aspects of facade performance (Jin, 2013, Ramachandran, 2004, Hendriks & Hens, 2000, Aksamija, 2013, Oliveira & Melhado, 2011, Rivard, et al., 1999), there is a lack of a holistic point of view that considers different aspects at once. It is believed that there is a need for an approach through which all factors, variables, conditions, constraints, and interactions/ conflicts can be seen/ addressed together.

A guide focusing the whole, rather than the fragments may have a positive contribution to both the product (facade) and the process (design). Instead of testing and evaluating a considerable number of alternatives via simulation tools or field studies in real conditions, to follow a model having holistic point of view in line with design goals and to reduce the number of design alternatives in early stages of design process to a lesser amount and near-ideal options and thereafter to carry out the evaluation accordingly may have a significant contribution to the facade design process. Being within different disciplines' area of interest makes it essential to design this building sub-system in a systematic way. There is not any single resource which guide the stakeholders for all these subjects. The stakeholders need to apply for separate resources during the facade design process. Nevertheless, it is possible to provide a holistic support in the early stages of facade design process by reorganizing the information/ knowledge available in the literature by means of various researches conducted by different disciplines with different points of view and by establishing the relationships in-between to constitute a meaningful whole.

Aim of the paper is to present (a part of) a tool developed to be used during the facade design process and counts functional performance aspects altogether. The tool provides a holistic systematic approach in order to support the design optimization. It is intended to assist decision-makers while giving decisions on facade parameters (design variables) to consider their interactions with functional performance aspects in possible environmental (outdoor) and spatial (indoor) conditions. It is expected to provide insight/ gives impression about facade performance as a whole. The tool highlights the interacting, conflicting issues of the process in order to see the whole with a holistic point of view. It bases on the relationships among performance aspects, conditions and facade parameters.

Briefly, the tool is believed to enable the decision-makers to trace the consequences of their design decisions holistically, to give the decisions in a transparent way by highlighting the compromises in design, and to support the communication among stakeholders. It is expected to assist design decision-making process and optimization in design, enable the stakeholders gain holistic point of view, and contribute to/ support the design of well-performing facades today and in future.

2 METHODOLOGY

The methodology followed throughout the tool formation is illustrated in Fig. 1. To develop the tool, firstly, detailed investigation is conducted on facade design and facade performance separately aiming at understanding the structure of the design process and the aspects of the performance (the upper part in Fig. 1 stands for it). A considerable amount of publications in the literature including books, e-books, journal articles, conference proceedings, theses, seminar/ course notes, standards, codes, regulations, commercial publications, encyclopedias, dictionaries, etc. are reviewed. Then, (the lower part in Fig. 1) the knowledge gained through the literature review is reorganized/ summarized in matrices by resolving, filtering and relating the information by keywords. In addition to this, expert opinions are gathered for rating the design options and weighting the relationships.

Functional performance aspects that are associated with biological/ physiological and social/ psychological requirements of the user are taken as the focus of the tool. The key performance aspects included in the tool are structural, fire, water related, air permeability related, thermal, moisture related, daylighting, and acoustic performances (Rich & Dean, 1999, Herzog, 2008, Boswell, 2013, Jin, 2013, ITU Seminar, 2013, Oraklıbel, 2014). On the other hand, the facade parameters that are taken as the main decision subjects within the tool are orientation (if it is left to be decided), transparency ratio, facade type, window type, glazing, framing, shading, wall configuration, finishing, and detailing. These parameters are defined after examining the facade design process in detail as analyzing the design decisions made in different design stages and architectural scales (T.R. Ministry of Environment and Urbanization, 2017, Boswell, 2013). Then, these design decisions are converted to key facade parameters.

The developed tool is in the form of spreadsheet designed via Microsoft Office software. First, for each facade parameter, design options are generated to keep the tool relatively simple and comprehensible. The design options are generated in accordance with the existing facade industry and knowledge. The options are not for limiting the flexibility in design, they are for guiding the

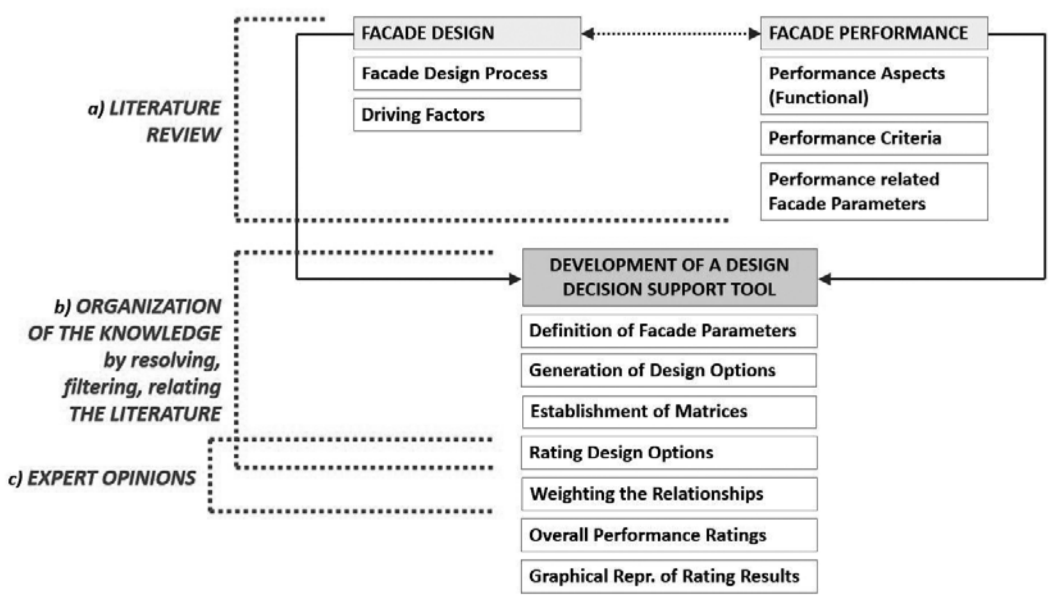

FIG. 1 Methodology followed throughout the tool formation

tool users (facade design decision-makers) to make deductions for their specific conditions. Then, matrices having design options in rows and performance aspects in columns are established. To support the decision-making, each intersecting cell in matrices proposes a rating (++, +, 0, -, --) or a rating prescription having conditional guidance (it also uses the same +, 0, - rating scale). So, the tool user is expected to rate each option in terms of each performance in accordance with the prescriptions. The tool not only proposes strict ratings, but also gives prescriptions that describes how to rate the options in possible environmental and spatial conditions. In other words, the tool adapts itself to different conditions. Within the context of the paper, environmental conditions represent location, climate, and surrounding (e.g. buildings, landscape, noise sources) while spatial conditions are for function of the building/ space, building height, spatial features of the room (e.g. room proportions, surface colours, heating, cooling, ventilation, and lighting systems). So, the prescriptions are taken shape around these conditions. Even though other significant factors such as budget, feasibility, etc. are kept out of scope, the tool gives the opportunity to compare the options for their price/ performance ratios by providing their performance footprints. Besides, decisions regarding aesthetics (it is not a technical function) are left to the users to be made according to the project context, architectural intentions, etc.

The rating proposed in the tool bases on comparisons and indicates how superior/ inferior is that design option (for that facade parameter) when compared to the others in terms of that specific performance aspect. If the option has direct advantage for that performance when compared to the other options, it can be given (+). Here, the 'direct advantage' means if the option is chosen instead of the other ones, the performance of the facade will be affected positively. On the other hand, if it has direct disadvantage for that performance, it can be rated as (-). If it has no direct effect, or negligible difference, which means there is no superiority among the options, it can be given (0). Besides, degree of superiority/ inferiority among options may increase for some environmental and/ or spatial conditions, then the values can be multiplied by 2 and become (++), (--), and (0). Consequently, the tool is composed of separate but interlinked rating charts designed for each predefined facade parameter. Some given decisions inevitably limit the options to be selected for the other decision subjects. These are prescribed within the charts, as well.

Moreover, an individual performance aspect is affected by more than one design decision. But, each design decision may have different weighted impacts on that performance. So, each relationship between facade parameters and performance aspects is weighted (6 for a strong relationship, 3 for a medium-strength relationship, 1 for a weak relationship). According to Cross (2008), assigning weights to relationships is one of the systematic design methods. The weights (1-3-6) proposed by Cross (2008) are adopted within the tool (see Tab. 1). First, the relationships are weighted by making inferences from the information in the literature. Then, the assigned weights are crosschecked with the expert opinions. These weights are embedded within the tool to test how it works. However, decision-makers, based on their specific design options (that can change the strength of relationships), may need to assign different weights. All the relevant adjustments can be made as long as they are grounded on the developed tool. The main idea is to assist the decision-making by this holistic systematic approach.

For the assessment of each single performance of a facade design; firstly, each rate given by the tool users is multiplied by its weight (the strength of the relationship between the decision subject and the performance aspect), secondly, these multiplied scores are accumulated with the assumption that the sum total of the design decisions composes the facade design.

DEGREE OF RELATIONSHIP (PROPOSED BY NIGEL CROSS)	NO DIRECT RELATIONSHIP		WEAK		MEDIUM		STRONG	
WEIGHTING	0		1		3		6	
Façade parameters & Performance rel.	Structural	Fire	Water	Air Permeability	Thermal	Moisture	Daylighting	Acoustic
Orientation	6	3	6	6	6	6	6	6
Transparency ratio	6	0	0	0	6	0	6	6
Façade type	6	0	3	3	6	6	0	3
Window type	1	3	1	1	6	6	6	1
Glazing	1	0	0	0	6	3	6	6
Framing	6	3	3	0	3	1	1	3
Shading	1	6	6	0	6	0	6	1
Wall configuration	6	6	6	6	6	6	0	6
Finishing	6	6	6	6	3	6	0	1
Detailing	6	6	6	6	3	6	1	6

TABLE 1 Weighting the relationships between facade parameters and performance aspects

3 TOOL

The tool bases upon the below triangular relationship (Fig. 2). The center of the triangle represents the decisions and the tool functions as a support for making these decisions. Facade parameters define the performance while performance requirements are specified based on the conditions. Therefore, facade parameters need to be specified in line with the conditions to provide the required performance.

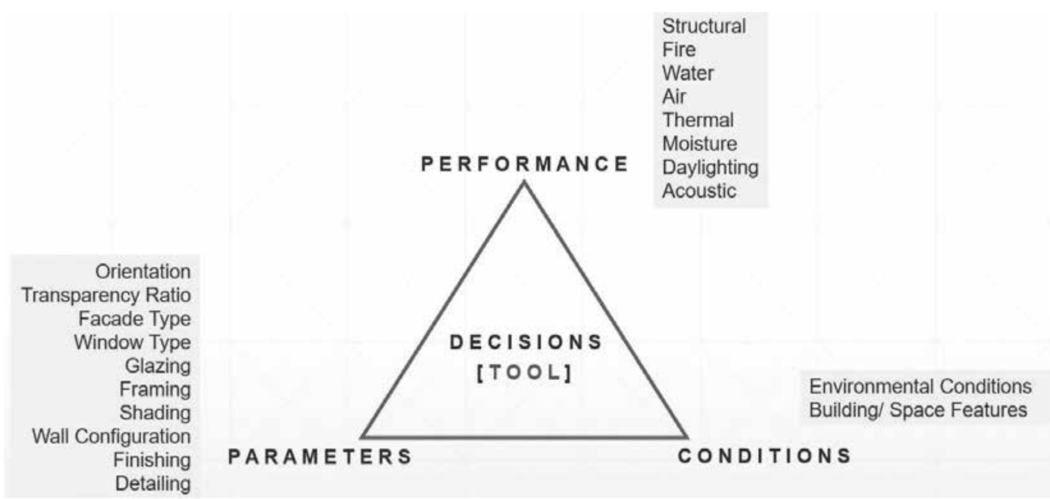

FIG. 2 Tool scheme

3.1 MATRICES

Separate but interlinked rating charts (matrices) are established for each predefined key facade parameter. The rating charts/ prescriptions, which belong to orientation parameter, are presented in this paper. Screenshots from rating charts are given in Fig. 3. The chart on the left (assume it without any rating) is the one that appears when the user clicks on the orientation decision subject on the tool's home page. Then, if the 'rate!' button under the thermal performance is clicked on, the chart on the right side appears. In this page, the user is expected to rate the options according to the given prescriptions. As soon as the options are rated, on the left chart, the empty cells are updated, and the tool highlights the ideal and worst options with a holistic point of view (based on the weights and the user's rates). Ultimately, the user is expected to make a choice by clicking on 'choose!' button. When the option is selected, the scores of that option is taken into account for evaluation.

The rating prescriptions for the orientation is given in Tab. 2. All the prescriptions in the chart are grounded on the information/ knowledge deduced from the literature. The options for the orientation are North (N), South (S), East (E), West (W), Northeast (NE), Northwest (NW), Southeast (SE), and Southwest (SW).

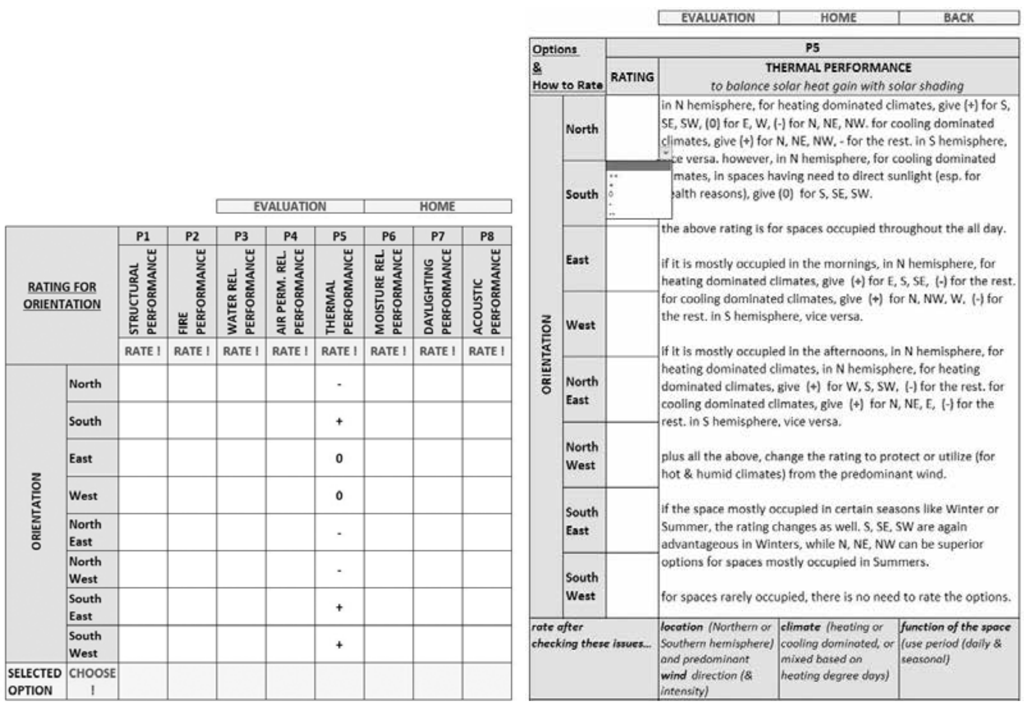

FIG. 3 Screenshots from rating charts (tool interface)

How to rate	Design Decision	ORIENTATION	Rate after checking these issues...
	Options	North | South | East | West | North East | North West | South East | South West	
P1	Structural performance	• give (-) for the options exposed to predominant wind directions (due to pressure & suction forces); (+) for the perpendicular directions; and (0) for the rest. • if it is high-rise building and wind intensity is high, multiply the rating values by (2). • if there is no predominance among the winds of different orientations, then there is no need for rating.	predominant wind direction (& intensity)
P2	Fire performance	• give (-) for the options exposed to the predominant wind directions; (+) for the most wind protected ones; and (0) for the rest. • if building function has high importance in terms of fire protection, then multiply the rating values by (2). • if there is no predominance among the winds of different orientations, then there is no need for rating.	predominant wind direction (& intensity)
P3	Water related performance	• give (-) for the options exposed to predominant wind directions; (+) for the most wind protected ones; and (0) for the rest. • if it is high-rise building and wind intensity is high, multiply the rating values by (2). • if there is no predominance among the winds of different orientations, then there is no need for rating.	predominant wind direction (& intensity)
P4	Air perm. related performance	• give (-) for the options exposed to predominant wind directions; (+) for the most wind protected ones; and (0) for the rest. • if it is high-rise building and wind intensity is high, multiply the rating values by (2). • if there is no predominance among the winds of different orientations, then there is no need for rating. • if stack effect dominates the air infiltration (in cold climates), there is no need to rate the options according to wind directions.	predominant wind direction (& speed) / building height (as high or low-rise)
P5	Thermal performance	• in N hemisphere, for heating dominated climates, give (+) for S, SE, SW; (0) for E, W; (-) for N, NE, NW. For cooling dominated climates, give (+) for N, NE, NW; (-) for the rest. In S hemisphere vice versa. However, in N hemisphere, for cooling dominated climates, in spaces having need to direct sunlight (esp. for health reasons), give (0) for S, SE, SW. • the above rating is for spaces occupied throughout the all day. • if it is mostly occupied in the mornings, in N hemisphere, for heating dominated climates, give (+) for E, S, SE; (-) for the rest. For cooling dominated climates, give (+) for N, NW, W; (-) for the rest. In S hemisphere vice versa. • if it is mostly occupied in the afternoons, in N hemisphere, for heating dominated climates, give (+) for W, S, SW; (-) for the rest. For cooling dominated climates, give (+) for N, NE, E; (-) for the rest. In S hemisphere vice versa. • plus all the above, change the rating to protect or utilize (for hot & humid climates) from the predominant wind.	location (Northern or Southern hemisphere) and predominant wind direction (& intensity) climate (heating or cooling dominated, or mixed based on heating degree days) function of the space (use period (daily & seasonal)
P6	Moisture related performance	• give (-) for the options exposed to predominant wind directions; (+) for the most wind protected ones (except N orientations in N hemisphere and S orientations in S hemisphere due to low solar radiation that reduces the drying potential); and (0) for the rest. • if it is high-rise building and wind intensity is high, multiply the rating values by (2). • if there is no predominance among the winds of different orientations, then there is no need for rating.	predominant wind direction (& intensity)
P7	Daylighting performance	• according to the function of the space, define which of the following is desirable: diffuse & homogeneous skylight (a) or direct sunlight (b). For a, in N hemisphere, give (+) for N, NE, NW; (-) for the rest (high glare potential). For b, in N hemisphere, give (+) for S, SE, SW; (0) for E, W; (-) for the rest. In S hemisphere, do the rating reversely. • if it has mainly winter and cloudy conditions during the year, then for some space functions, sky illuminance may not be sufficient in N orientations in N hemisphere. Check the latitude & climate and make the relevant adjustments (e.g. give (0) for N, and (+) for NE, NW). For b, give (+) for S since it provides direct sunlight and relatively easier to control; give (0) for E, W, SE, SW for providing low-angle direct sunlight which is hard to control in terms of glare; give (-) for the rest. • plus all above conditions, surrounding obstacles (buildings, trees, etc.) or view change the rating. Highly reflective surrounding surfaces (including the ground) may contribute to the illumination levels or a pleasing view may be a desire. Adjust the above ratings accordingly. • for spaces rarely occupied, there is no need to rate.	location (Northern or Southern hemisphere, latitude) / climate surrounding obstacles (& solar reflectivities) /view function of the space (type of activity)
P8	Acoustic performance	• give (-) for the options in the direction of noise sources; (+) for the most noise protected directions; and (0) for the rest. • if the space is highly noise-sensitive, then multiply the rating values by (2). • if the space is rarely used, there is no need for rating.	surrounding noise sources and function of the space (use period, noise sensitivity)

TABLE 2 Rating prescriptions for the orientation

3.2 TESTING

The tool is tested with a case study (sample facade design) in Istanbul, Turkey. The key environmental conditions and spatial features are remarked in the tool as to be checked before rating. These features of the case study are given as follows. The case study is in Üsküdar, Istanbul, Turkey (Northern hemisphere). Istanbul has a heating-dominated climate. It has kind of a mild climate (temperate-humid) in which there are no extreme day-night temperature fluctuations. Predominant wind directions are Northeast and Southwest. There is a city panorama on the Northern side while there are mid-rise office buildings on the South and East directions. There is a highway (dense traffic) on the Northern side. The facade in question encloses a classroom which is at the first floor of a k-12 school building (low-rise). The classroom is mostly occupied in Winter periods.

The design options (for orientation) in the predominant wind directions are given (-) for structural, fire, water related and air permeability related performances in accordance with the rating prescriptions. Northern orientations (N, NE, NW) are given (-) for not taking advantage of solar radiation while Southern orientations (S, SE, SW) are given (+) for providing maximum amount of sunlight. The rest are assumed as mediocre options and given (0). For moisture related performance, the options in the predominant wind directions are given (-), the most protected ones are given (+) except for NW (it is given (0)), and the rest are given (0). For daylighting performance, S is given (+) and SE, SW, E, W are given (0) for having glare risk. N is given (0) since it provides homogenous but not sufficient daylight, so one advantage plus one disadvantage make it neutral (0). NE and NW are given (-) assuming that they have the disadvantages of both insufficient daylight and glare risk. Lastly, for acoustic performance, the Northern orientations are given (-) for being in the traffic (potential noise sources) side while the opposite directions are given (+), and the rest are given (0).

RATING FOR ORIENTATION		P1	P2	P3	P4	P5	P6	P7	P8
DESIGN DECISION *(building scale)*	Options	STRUCTURAL PERF.	FIRE PERFORMANCE	WATER REL. PERF.	AIR PERM. REL. PERF.	THERMAL PERF.	MOISTURE REL. P.	DAYLIGHTING PERF.	ACOUSTIC PERF.
		RATE !	RATE !	RATE !	RATE !	RATE !	RATE !	RATE !	RATE !
ORIENTATION	North	0	0	0	0	-6	0	0	-6
	South	0	0	0	0	6	0	6	6
	East	0	0	0	0	0	0	0	0
	West	0	0	0	0	0	0	0	0
	North East	-6	-3	-6	-6	-6	-6	-6	-6
	North West	6	3	6	6	-6	0	-6	-6
	South East	6	3	6	6	6	6	0	6
	South West	-6	-3	-6	-6	6	-6	0	6
SELECTED OPTION	North West	6	3	6	6	-6	0	-6	-6

IDEAL OPTION	**for that specific condition, the most advantageous orientation is **SE** in terms of overall facade performance.*
WORST OPTION	**for that specific condition, the most disadvantageous orientation is **NE** in terms of overall facade performance.*

FIG. 4 A representative spiderweb chart

4 RESULTS

The proposed tool can be regarded as a user-friendly tool since the tool user just need to follow the prescriptions, almost taking no initiative, and it takes approximately ten minutes to rate the options for a single design decision (here it is the orientation). The results of the tool testing for orientation is presented in Fig. 4. The options are rated according to the environmental conditions and spatial features of the case study. For instance, since there is traffic noise on the Northern side, these options are given (-), which in turn multiplied by its weight and turns into (-6). Another example is that Southern directions are given (+) for thermal performance based on the prescriptions provided within the tool. On the other hand, if the case was in Southern hemisphere, the results would be completely different for thermal and daylighting performances, such as the N option would be advantageous.

The tool gives the ideal design option(s) for each decision subject (here for orientation) based on the rates and weights. The ideal option of the tool stands for the best option when considered all the performance aspects holistically. However, it is not always possible to choose the ideal option proposed by the tool. It may be due to space organization, land settlement, etc. Under these circumstances, the tool implicitly recommends paying attention to the inferior performances in other design decisions (facade parameters). Here, while the ideal option is Southeast, the selected option is Northwest which is neither the ideal nor the worst one. The ratings of the selection indicate that thermal, daylighting, and acoustic performances should be paid attention at least in making decisions for other facade parameters. The numbers are calculated by the tool itself. The tool user just needs to check the highlighted parts (ideal and worst options) and compare the rest as bigger or smaller numbers.

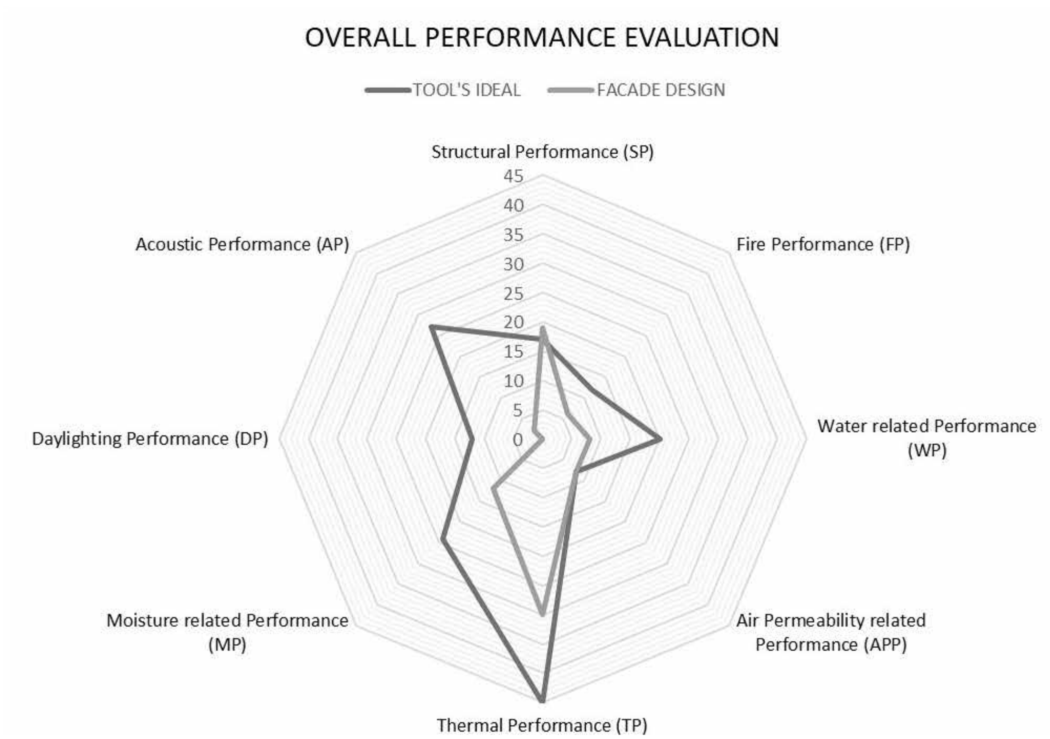

FIG. 5 A representative spiderweb chart

Finally, the scores obtained from separate charts are accumulated (the sum of + and - is 0, one advantage plus one disadvantage make the design neutral) for the overall performance evaluation of facade design. Then the results are illustrated by a spiderweb chart (the format is given in Fig. 5). The final spiderweb graphic, which includes separate sections for each performance aspect, gives the opportunity to compare the facade design alternative with the tool's ideal. The tool does not give real performance values, instead it relatively compares alternative designs in terms of performance aspects and provides their overall functional performance footprints. Tool's ideal appears as soon as the user completes to rate the options for all facade parameters. It does not represent an absolute ideal and it assumes that all the facade functions are equally important, so it approaches the facade performance holistically without overlooking any functional aspect. On the other hand, in some cases, one performance aspect of the facade may be given much more importance than the rest. In that case, the results of the tool (performance footprints) can be interpreted accordingly.

5 CONCLUSIONS

The tool is believed to provide insight about the entire facade performance while addressing the interactions, conflicting issues among separate performance aspects and their relationships with design decisions. Thus, it will lead to a holistic facade design, better trade-offs, and transparency in decision-making, especially in early stages of facade design process. Consequences of design decisions regarding facade performance can be traced holistically. Design is a process of limiting possible alternatives and here the tool may function as a supportive guidance. By having the potential to prevent negative iterations in the design process, it will be time-saving, as well. Although the decisions need to be finalized by integrating some other issues like costs, and aesthetic features of the design alternatives, by means of the tool, options can be compared in terms of their functional performances. Besides, the tool provides the notion of how (by changing which design decision(s)) to improve the performance of the final design. Project conditions may vary, so the importance factors of the performance aspects. In that case, design decisions can be given accordingly which makes the tool flexible to changing priorities/ conditions. In future studies, design options within the scope of the tool can be expanded and rated by following the similar logic. Furthermore, the tool can be customized for specific climatic conditions, or building/ facade types. It may evolve in future, as new knowledge is incorporated into the tool.

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Arkol – Development and testing of solar thermal venetian blinds

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Abstract

The idea of removing solar thermal heat from the building envelope dates back to Morse (1881). Building-integrated solar thermal (BIST) collectors for opaque building envelope areas have since become available in various forms, albeit far fewer than for transparent BIST collectors. Modern architecture's predilection for highly transparent facades, however, has led to an increased demand for new glazed-area BIST solutions.

The Solar Thermal Venetian Blind (STVB) being developed by Priedemann Facade-Lab and Fraunhofer ISE as part of the ArKol R&D project (Architektonisch hoch integrierte Fassadenkollektoren mit Heat-Pipes) aims to combine the advantages of venetian blinds and solar thermal collectors. The hope is that these may even be enhanced due to various symbiotic effects. STVBs have the clear advantage of collecting solar energy for use in domestic hot water, solar heating and cooling. Additionally, STVBs can actively reduce the heat flux to the building interior, decreasing the cooling load and improving thermal comfort thanks to lower surface temperatures.

Heat pipes are used to extract the absorbed solar energy from the venetian blind slats. These are connected to vertical header tubes via a dry connection, requiring just two hydraulic connections per facade element and allowing the slats to be operated in the same manner as a typical venetian blind.

This paper explains the development of a 1:1 demonstrator as a full-size unitized facade element with integrated STVB. An interdisciplinary approach was used, with collaborative 3D planning and simulations by the project partners, ensuring a highly evolved facade element for outdoor testing. At the time of writing, the demonstrator was completed and undergoing testing. Results were predicted to provide important information for further research and development in areas including: (1) identifying problems and solutions for the construction, production and assembly of STVBs; (2) STVB performance; and (3) improvements in facade performance due to STVB integration. Both the demonstrator and its results will be used to involve relevant external partners and stakeholders via innovative workshops and upcoming building construction trade fairs.

Keywords

Solar thermal venetian blind, building-integrated solar thermal (BIST), multifunctional sun-shading, energy harvesting facade, double skin facade, facade demonstrator

1 INTRODUCTION

Building-integrated solar thermal (BIST) collectors use the available space of the building envelope to fulfill several functions, including the supply of solar thermal heat (Maurer, Cappel, & Kuhn, 2017). Most conventional BIST systems are opaque (IEA SHC Task 51, 2016). Semi-transparent BIST collectors also exist, but these are stationary and hence seldom used when visual contact with the exterior is prioritised (Fuschillo, 1975) (Cappel, et al., 2015) (Maurer, Cappel, & Kuhn, 2017). However, many buildings use venetian blinds within the transparent area of the building envelope for solar control (Kuhn, 2017). By adding solar thermal collector functionality, the venetian blind can act as a solar thermal collector while maintaining its solar control functionality. A venetian blind with an integrated solar thermal collector – the so-called Solar Thermal Venetian Blind (STVB) – has the following general functions:

- Supply of solar thermal heat
- Similar or improved solar control functionality compared with a conventional venetian blind (Kuhn, 2017)
- Similar or improved g-value compared to a facade with a conventional venetian blind
- Similar or improved facade functionality compared to a facade with a conventional venetian blind

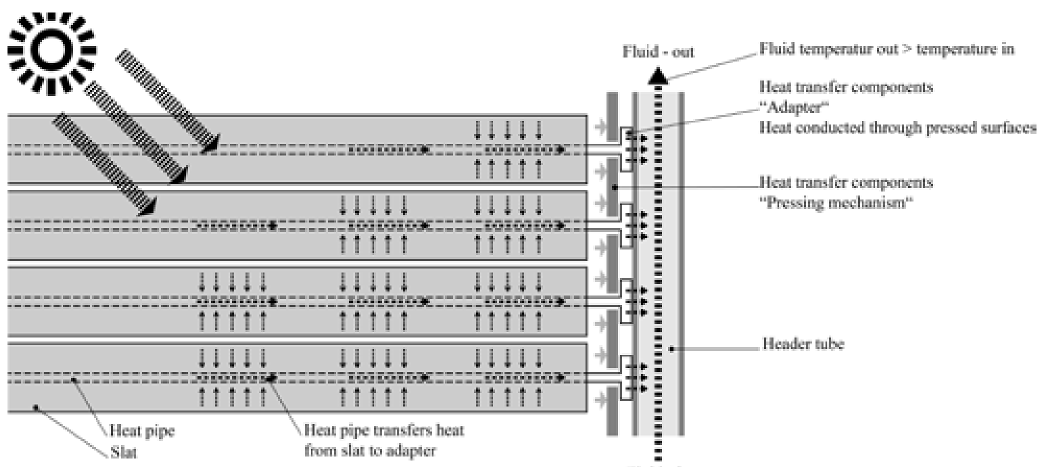

FIG. 1 Main components of an STVB. The mechanism for retracting and tilting the slats is not shown © Priedemann Facade-Lab

The general working principle of an STVB is as follows (see Fig.1): solar irradiance is absorbed by the upper surface of the slat and transferred to the underlying heat pipe. Each heat pipe then transfers the heat to its condenser. Here, the heat is transferred to the header tube using "heat transfer components." The two main components are adapters – media that transfer heat from the heat-pipe to the header tube – and a pressing mechanism that controls the position and operation of these adapters. Fluid (e.g. water) flows within the header tube and transports the heat to the building services, where it can be used in various applications (Maurer, et al., 2013). Heat transfer components transfer heat via a dry connection, with no fluid transfer. This allows the STVB slats to be movable, in the same way as a conventional venetian blind (i.e. the slats can be tilted, retracted or lowered). Under the current design, when the slats are lifted or tilted the adapters are released from the header tube surface, stopping the heat transfer between the elements. This switchable coupling allows for the movement of the slats. Once the slats are in the desired position, the pressing frame automatically pushes the adapter onto the header tube surface, allowing the heat transfer to continue.

A functional facade demonstrator with an integrated STVB has recently been developed (Fig. 2). The system was installed in the cavity of a double-skin facade (DSF) element with a realistic size of 1.4 m wide and 3.6 m high. The facade demonstrator "LabTestSample" would later evaluate the facade's thermal performance and the collector's solar thermal yield based on measurements obtained from the Outdoor Test Facility for Real-Size Building Envelope Elements (OFREE) at Fraunhofer ISE (Fig. 3). With OFREE, the facade can be tested under different orientations and inclinations using a rotatable and tiltable base. Behind the test object is a measurement surface that occupies most of the facility surface area and is able to detect temperature differences and heat flux through the element in various parts of the demonstrator. At the time of writing, no test results are available. However, the OFREE LabTestSample is expected to be completed by the end of 2018, and results published by mid-2019.

The LabTestSample was constructed based on a DSF system identified as a suitable facade type for STVBs. DSF protects the STVB from wind, dust and human contact (Knaack, Klein, Bilow, & Auer, 2014), leading to longer life expectancy, reduced maintenance, and the capacity to function in strong winds. A higher thermal yield can also be achieved, as a closed cavity creates minimum heat loss from the absorber and the heat-pipe surface (Wolf & Molter, 2012). The DSF cavity tends to overheat under solar radiation. Glass with a high insulation property (e.g. triple glazing) would thus be required for the inner surface that acts as the barrier between the cavity and the interior space. The prediction is that STVBs will have the potential to absorb and bring out this heat, reducing the heat coming directly from the cavity. This could result in a smaller requirement for glass insulation and a lower cooling load for the interior space.

The LabTestSample will be exhibited at various upcoming trade fairs to relevant stakeholders (e.g. industrial partners, suppliers, sun shading producers, metal fabricators, distributors, architects, specialized planners and investors). Based on outcomes and test results, in combination with stakeholders' knowledge and experience, an innovative facade solution is anticipated (Klein, 2013).

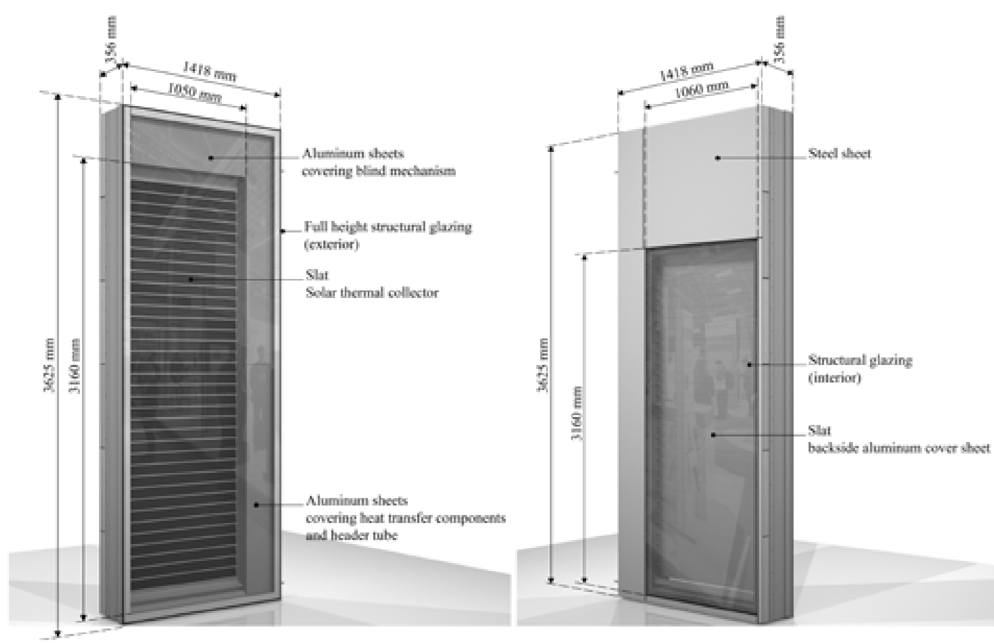

FIG. 2 LabTestSample of an STVB integrated into a double-skin unitized facade element. Exterior view (left). Interior view (right) © Priedemann Facade-Lab

FIG. 3 OFREE without test sample. The black area is the measuring surface (left). The completed LabTestSample mounted on OFREE (right) © Fraunhofer ISE

2 METHODOLOGY

The STVB has to function simultaneously as a building-integrated solar thermal collector and solar control system. STVB design parameters were thus investigated to analyze the different technical possibilities. An overview of the design parameters and general evaluation criteria for BIST collectors was published by Cappel et al. (2015). A design parameter space for solar control systems was established by Kuhn (2017) , in which different evaluation criteria could be applied. All design parameters were linear, independent, and accommodating to all design possibilities. The choice and weighting of the evaluation criteria was dependent on the application in question (e.g. building type and usage). Aside from technical functionality, the development and design of STVBs is subject to architectural and aesthetic conditions that are crucial for acceptance and market success. The BIST criteria (functionality, aesthetics, ecology, economy and feasibility (Cappel, et al., 2015)) were thus applied during the development process, as were the evaluation criteria for solar control systems (Kuhn, 2017). As stated above, the exact definition and weighting of the different evaluation criteria depends on the application in question. The functionality of the STVB can, for example, be evaluated with regards to the supply of solar heat, thermal comfort and glare protection. Similarly, ecology can be analyzed and evaluated in terms of primary energy savings. For the current STVB design, the following categories were considered. Where possible, these will be subject to qualitative and quantitative evaluation:

- Solar thermal yield [W/m^2]
    - Absorbed radiation
    - Heat transfer to fluid in the header tube
    - Heat losses to surroundings
- Solar control
    - Cooling load demand of building/ solar heat gain [kWh/a]
- Auxiliary energy demand [kWh/a]
- Cost [€]
- Availability of components
- Temperature stability [°C] and durability of components [a]
- Reliability
- Slat packing thickness [mm]
- Slat weight [kg]
- Slat stability [mm]
- Transparent area of STVB element [%]
- Safety of room occupants

3 EXPERIMENT/ RESEARCH

3.1 STVB DESIGN

3.1.1 Position of the STVB

Of the three facade integration positions – external, internal and in the cavity between the glazing layers (Haeringer, Camarena, Vongsingha, et al., 2017) – mounting the STVB within a cavity of a DSF is the most suitable choice, as it is protected against weather conditions and can be contacted directly by users.

The solar thermal yield is increased by keeping the air in the cavity with low or zero heat exchange (e.g. closed cavity facade) with the surroundings. Compared with a single-skin facade, there is less heat loss when the air is contained in this manner. To increase occupants' comfort, the STVB reduces the temperature in the cavity – a critical aspect of a DSF – by absorbing the heat and bringing it through theabsorber, heat pipe and header tube. These two objectives should be optimized and balanced to provide the maximum solar thermal yield, leading to improved environmental conditions for occupants.

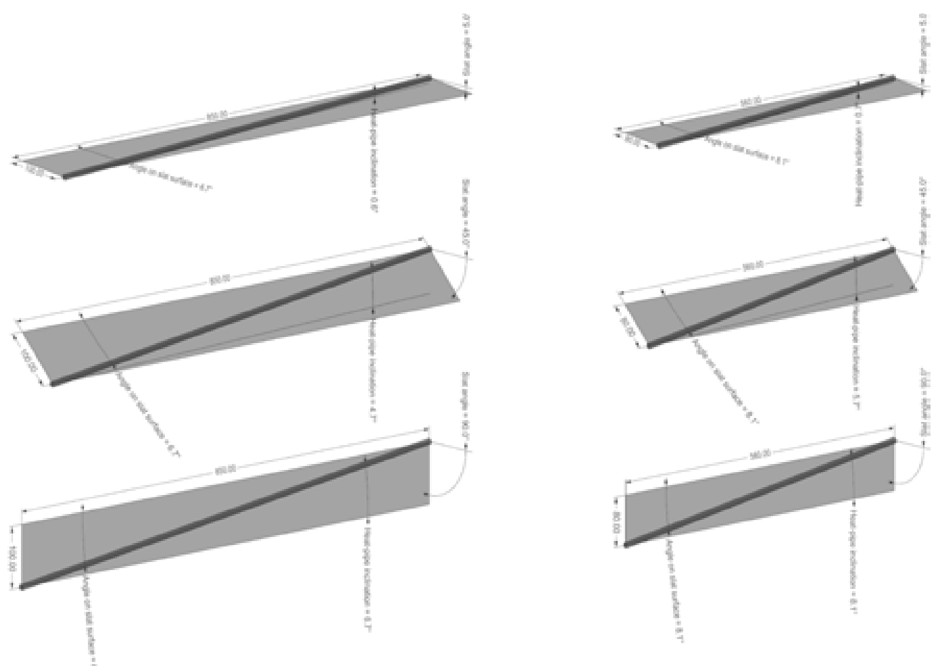

FIG. 4 Slat and heat pipe angle analysis. See Table 1 for results © Priedemann Facade-Lab

SLAT SIZE	SLAT TILTING ANGLE	HEAT PIPE INCLINATION
560 x 80 mm	5.0°	0.7°
	45.0°	5.7°
	90.0°	8.1°
850 x 100 mm	5.0°	0.5°
	45.0°	3.8°
	90.0°	5.4°

TABLE 1 Heat pipe inclinations in correlation with various slat dimensions.

3.1.2 Slats

Fig. 5 shows the design of the slat with its individual components. The slats have a significant influence on solar thermal performance, aesthetic appearance and structural stability.
A commercially available copper heat pipe (8 mm diameter) and a copper absorber sheet (0.2 mm thickness) were combined using laser welding to achieve a lamella thickness of 10 mm. The heat pipe was positioned diagonally to the absorber plate to retain the height difference between the evaporator and the condenser when the slat is inclined. The heat pipe works at nearly 0° inclination, although its thermal performance increases in line with the operating angle (Morawietz, Röschl, Halim, Paul, & Hermann, 2016). Analysis of the heat pipe angle in correlation with the slat dimensions was hence carried out to determine the optimal collector performance and blind requirements (see Fig. 4).

At one end of the heat pipe, the condenser was pressed inside a solid aluminum adaptor. Heat released from the heat pipe condenser is conducted through the adapter and to the header tube via surface heat transfer. The contact area of each adapter to the header tube was 12 x 100 mm. As in Fig. 5 and Fig. 7, the adapter fins transfer the pressing force from the pressing mechanism to the adapter/ header tube surfaces.

An earlier 1 x 1 m mockup showed that given the weight of the heat pipe and the adapter, the slat required extra reinforcement to avoid deformation (Haeringer, et al., 2017). In the current LabTestSample, the stability of the slat was increased using additional aluminum beams, a back cover sheet, and spacers at either end of each slat. The back cover sheet was designed to cover the visible heat pipe, and to influence the interior appearance of the STVB. The spacers serve mainly as a holder for the upper slat to prevent it from scratching the surface of the lower slat's absorber sheet when the blind is in a packed position and to attach the tilting mechanism to each slat.

The LabTestSample has a total of 37 slats. Each is 1.2 m long and 94 mm wide, with a 0.07 m^2 absorber surface, corresponding to a total absorber area of 2.7 m^2 for the entire facade element (~5m^2).

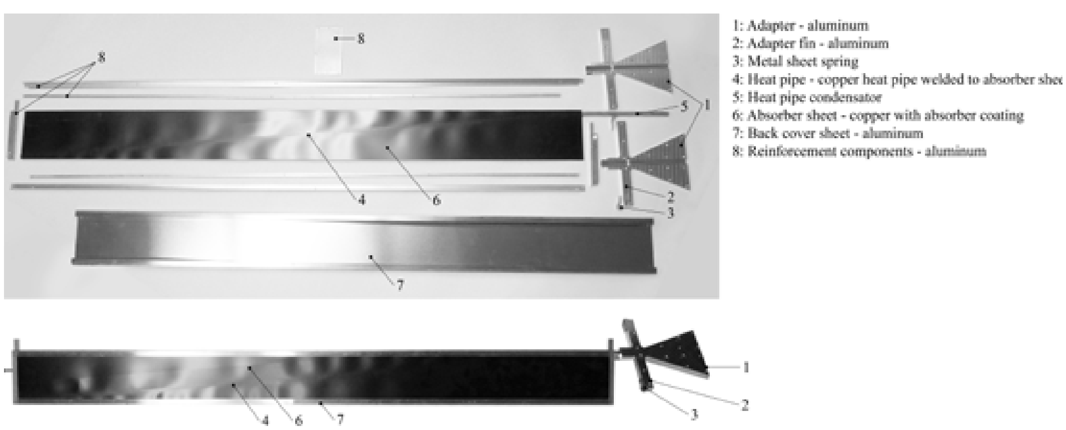

FIG. 5 Slat components. Heat pipe laser welding is slightly visible on the absorber sheet © Fraunhofer ISE

Future slat design possibilities were investigated to meet the state-of-the-art demands for venetian blinds (Kuhn, 2017). The architect, client and planning team were given a variety of geometrical options that varied according to price and appearance, as described by Denz, Vongsingha, & de la Fuente (2018).

3.1.3 Heat Transfer Components and Header Tube

Heat transfer between the heat pipe condenser and the header tube is one of the most challenging functions for an STVB (Haeringer, Abderrahman, Denz, et al., 2017). The switchable thermal coupling was designed and developed to ensure high thermal conductivity between two separable and movable elements.

The switchable thermal coupling was implemented by pressing and releasing springs and solenoids, respectively, to transmit the force to the adapters by moving the pressing frame. Both the adapter – a solid element – and the pressing frame were made out of aluminum, as it weighs less, is less corrosive, and has better surface roughness than steel or copper. They were designed to be able to transmit a contact force of approximately 10 N per adapter at all slat tilting angles. Activation of the solenoids requires a short current pulse of 24 V for less than a second. Once in their pressed-on state, the solenoids release the contact, allowing the slat to move freely. Once the slats are in their new positions, another short electric pulse deactivates the solenoid and returns the system to a closed position in which the heat transfer begins again. No additional energy is required to sustain the contact between the adapters and the heat pipe in the closed position.

The header tube transfers heat from the adapters to the heat transfer medium, such as water or solar fluid (i.e. water-glycol mixture). The heat is then transferred to the building service system. The heat transfer from the adapters to the header tube is influenced by both contact surfaces. Transfer from the header tube to the fluid relies only on the geometry of the header tube cross section. Increasing the contact area between the fluid and the header tube material therefore ensures a more efficient transfer process.

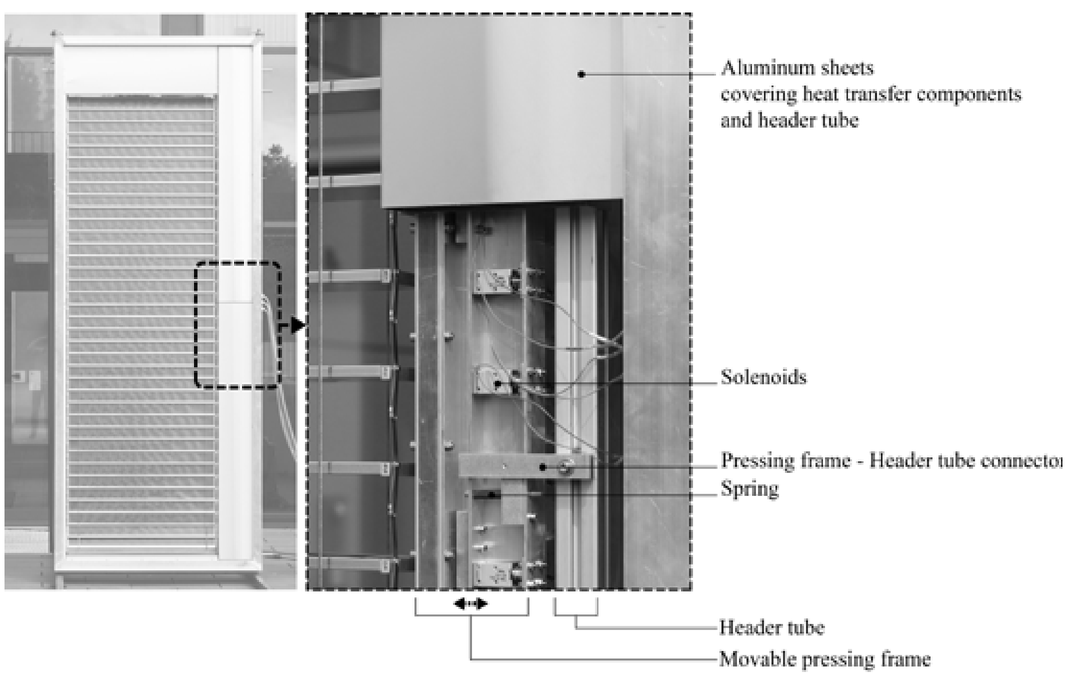

FIG. 6 Heat transfer components after assembly. See Fig. 7 for more detail (cross section) © Fraunhofer ISE and Priedemann Facade-Lab

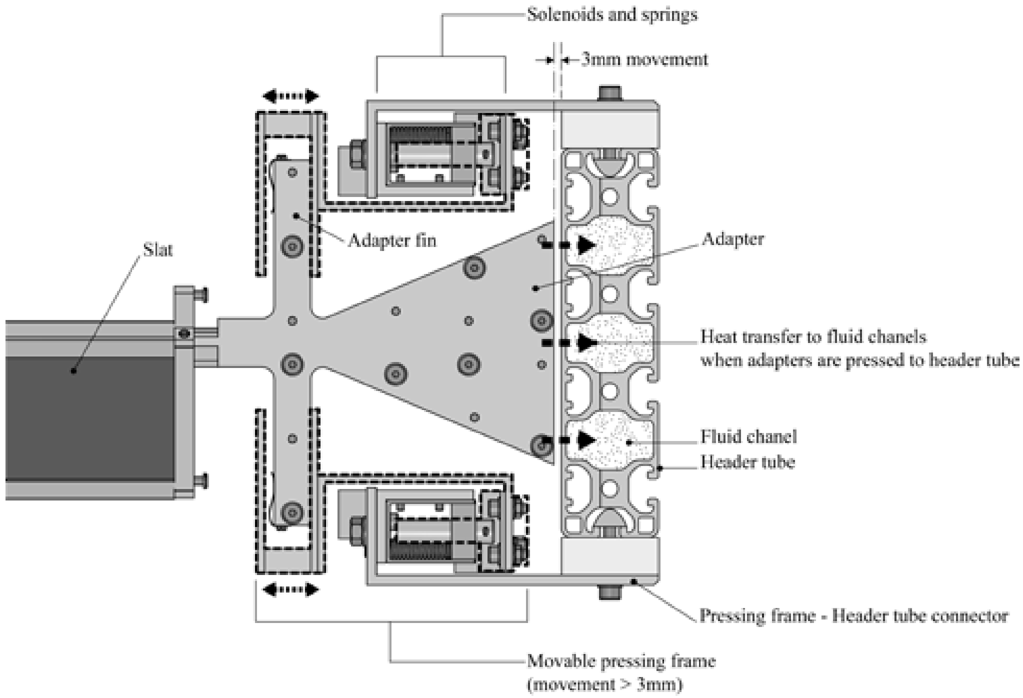

FIG. 7 Heat transfer components: Switchable thermal coupling between the slats and the header tube © Fraunhofer ISE and Priedemann Facade-Lab

Structural analysis indicates that the fluid pressure of the solar thermal system, can lead to a slight deformation of the surface of the header tube. If the surfaces of the adapters and the header tube are not aligned, the contact surface properties will be lower, resulting in less efficient heat transfer. In the current header tube design, aluminum multi-port extrusion (MPE) was applied to reduce the aforementioned surface deformation. MPE also increases the contact surface between the fluid and the header tube, improving the quality of heat transfer between the two materials.

3.1.4 Blind Mechanism

The slats weigh approximately 1 kg each, including the adapter, and their exact horizontal alignment is crucial for the heat transfer system. A standard blind mechanism featuring a motor with a textile rope for lifting and tilting is therefore not appropriate. Instead, steel wire ropes and scissor chains were used for the lifting and tilting mechanism. The scissor chains were of the kind normally used in heavy venetian blind systems, such as those with steel slats (e.g. Metalunic (Griesser AG, 2018)) whose functionality combines providing shade and protecting against burglary.

The steel elements were applied to the LabTestSample to minimize the elongation caused by the weight of the slats. This is particularly important as the weight of each slat is not evenly distributed, and the slat would hang obliquely if the length of the tilting elements became uneven. The bottom rail was an aluminum component with a specially designed 135° angle bended plate. The rail was incorporated into the stacking position of the slats and adapters, which have 45° difference in their respective tilt. To ensure that all adapters had the same pressing properties, the motors and the bottom rail were brought together by the pressing frame. The movement of the motors and the bottom rail ensure that no restoring force will pull the blind back into an open position.

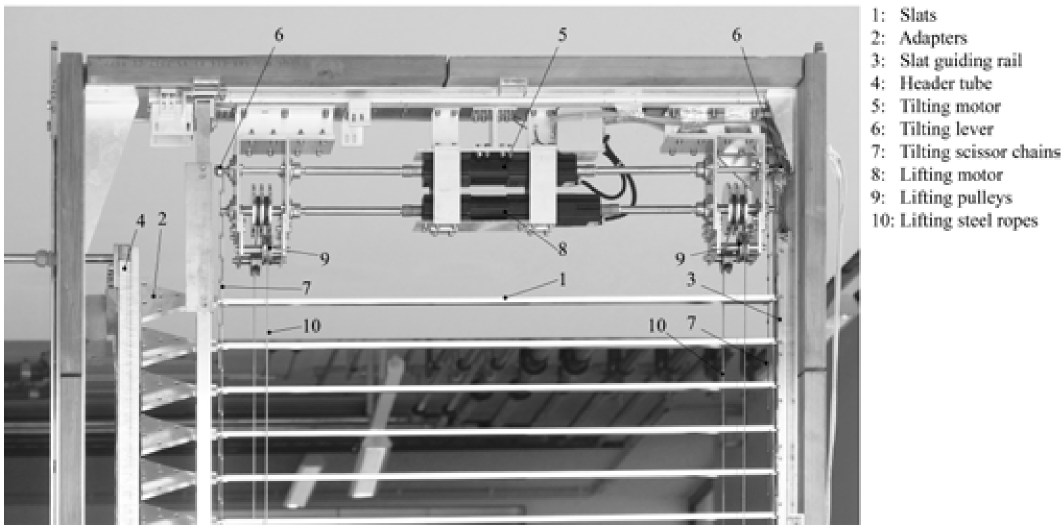

FIG. 8 Blind mechanism mounted inside the facade element. The pressing frame is not yet mounted © Fraunhofer ISE

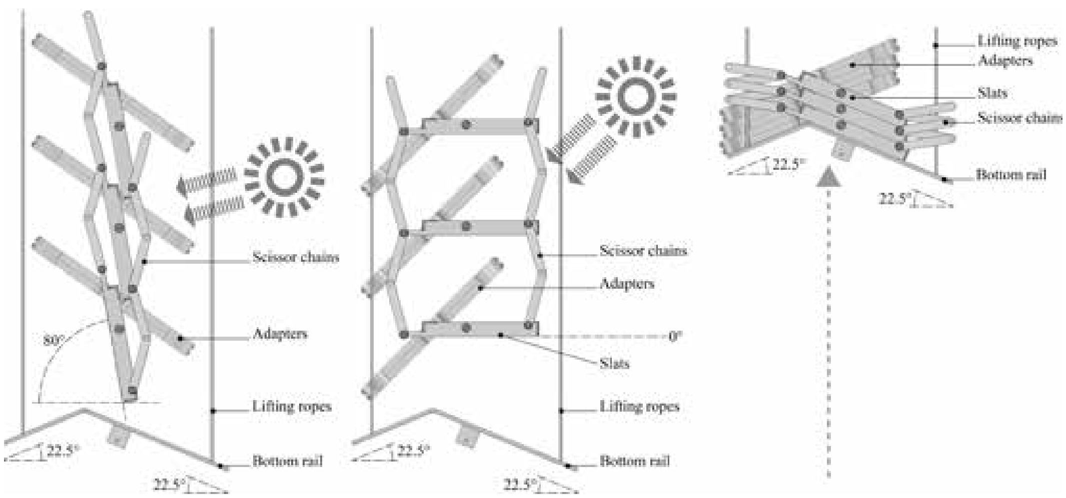

FIG. 9 Slats, scissor chains and bottom rail in different positions according to the angle of the sun © Priedemann Facade-Lab

3.1.5 Control System

The design of the STVB control system seeks a compromise between a high solar thermal yield and high user comfort. While an automated control system can maximize the solar thermal yield, it can lessen user comfort for reasons including reduced view, low quality daylight conditions, or unexpected movement of the slats. To address these comfort issues, users should be able to partially override the control system or optimize the settings according to subjective preferences or room functionality.

3.1.6 Facade Element

In the LabTestSample, an STVB was installed into a 3.6 x 1.4 m frame to mimic the performance of a unitized facade element. However, the element was designed and assembled with basic aluminum profiles. The outward facing aspect used a full-size (1.4 x 3.6 m) single layer (without lamination) thermally tempered safety glass (TSG) as clear glass of 8 mm thickness. As the system is intended for use in a high-rise building, the selection of the glass has to be adapted to the facade system. For example, in case of maintenance of the STVB from inside a sufficient fall protection needs to be ensured, which is not given with a TSG. However, clear TSG was chosen for Labtestsample because it has high UV-transmission which could improve the performance of STVB, unlike laminated glass, which absorbs UV light through the lamination foil. A possible alternate solution for use in a real-life setting is high UV-transmittance laminated glass of the type used in green houses or winter gardens (e.g. DuPontTM SentryGlas® (E. I. du Pont de Nemours and Company, 2018)).

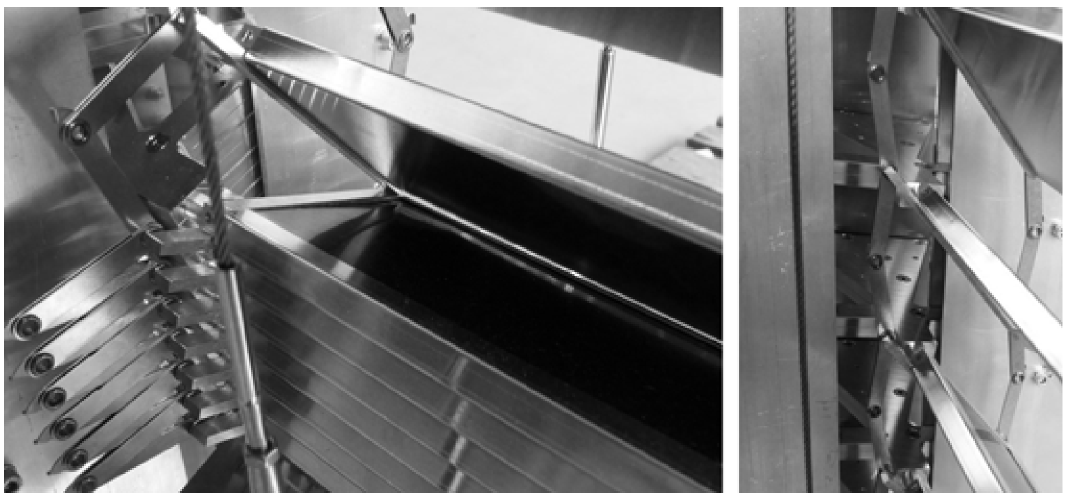

FIG. 10 Scissor chain tilting mechanism and lifting steel rope mounted on slats. The slats are being packed, and the adapters are partially visible (left). The slats are in an open position (right) © Fraunhofer ISE

The inner glazing is an insulated double glazing unit, with a laminated layer facing the interior. Its build-up consist of TSG 4 mm with low-e coating facing the inside, 16 mm of Argon filled intermediate space and a laminated safety glass consisting of 2 x 4 mm float plus 1 layer of PVB foil. Thus leading to a Ug-value of 1.1 W/m²K. Its exterior view was provided by a 2.6 x 1.1 m opening equivalent to 60 % of the façade area. To increase the precision of the measurement obtained via OFREE, the whole surface of the back side of the LabTestSample must be flat and positioned 10 mm away from OFREE's measuring surface. Glass with clamping is hence unsuitable in this instance.

The cavity between the inner and outer glazing was approximately 300 mm wide where the STVB was installed. Besides the STVB, the cavity contained thermal insulation and cover sheets surrounding the pressing mechanism.

The LabTestSample design did not include a ventilation system such as a DSF or a pressurizing dehumidification system, as for a closed cavity facade (Permasteelisa Group, 2014). It was designed, rather, to use solar heat and an external heating system to increase the temperature in the cavity and get rid of condensation (in a similar manner to a typical flat plate solar collector). Ventilation was achieved through a small opening filled with insulation. The aim was to create sufficient tolerance for thermal expansion inside the cavity, with negligible influence from the outside temperature.

PRODUCT TYPES	PRICE RANGE	CROSS-SECTIONS
Type 01: Rectangular aluminum profile (without absorber sheet)	€	
Type 02: Basic geometry with straight absorber sheet	€€	
Type 03: Complex geometry with one side bent absorber sheet	€€€	
Type 04: Complex geometry with two sides bended absorber sheet	€€€€	

TABLE 2 Various slat geometries © Priedemann Facade-Lab.

3.2 FURTHER STVB CONCEPTS

Alternative switchable thermal coupling is currently under development, in parallel to the LabTestSample. A camshaft actuator (Nungesser, 2018) seems to be a reliable alternative to springs and solenoids. The camshaft system consists of a main rotating shaft with cams in two directions that press and release the pressing frame. The system is operated by a motor that rotates the shaft. Early indications from the demonstration camshaft are that the switchable thermal coupling is much smoother and quieter compared to the current system. The movement of the pressing frame is slower, but initial tests show that it can provide a greater pressing force, resulting in improved heat transfer. Another development relates to the aesthetics of the STVB slats. Results of this research could lead to less visible, smoother and more streamlined slats, as shown in Tabel 2.

Beyond the Arkol project, various developments regarding different absorber coatings are ongoing. For example, by lowering the absorption efficiency, a wide variety of colors could become available (Bläsi, Kroyer, Hoehn, Ferrara, & Kuhn, 2016). Similarly, an absorber that reflects the visible range of light and absorbs the majority of the infrared radiation (Lang, 2018) may have a possible application in STVBs. Most of these developments have a high potential for replacing the conventional absorber coating used in current STVB design, adding value for both clients and architects alike.

The performance of conventional heat pipes is dependent on their orientation, with higher tilting angles leading to better performance (Morawietz, Röschl, Halim, Paul, & Hermann, 2016). Currently, this is achieved by the diagonal positioning of the heat pipe along the slat. However, were a functional horizontal heat pipe to become available, it could have a significant influence on slat design and hence the entire STVB. For example, the heat pipe could be mounted along the slat's center line, simplifying its appearance and functionality. This in turn could lead to a smaller cavity and installation space. The slat could even be produced as a single heat pipe.

4 CONCLUSIONS

STVBs integrate solar thermal collector functionality into fully glazed building envelopes while acting as a solar control device. The design parameters and lessons learnt from the LabTestSample indicate that future STVB development will be based on the following considerations: (1) the position of the

STVB inside the cavity of the DSF; (2) heat transfer from the slat via contacted surfaces without fluid exchange, where the heat pipe and the switchable thermal coupling are the main components; and (3) a multi-pot header tube to ensure less deformation due to liquid pressure. Other options, such as a horizontally oriented heat pipe, the use of a camshaft as an actuator for the pressing mechanism, different types of absorber coating, and alternative slat geometries may also be integrated into future STVB design. Solar thermal yield and heat transfer through the facade element are due to be tested in LabTestSample, with the results being implemented in a simulation model. Based on this model, different building performance simulations will be carried out as part of the quantitative assessment of STVB variants.

5 OUTLOOK

As of October 2018, the construction of the LabTestSample is complete. However, significant tuning and readjustment is required to ensure the best contact surface between the adapters and the header tube. The LabTestSample will be tested soon at the Outdoor Test Facility for Real-Size Building Envelope Elements (OFREE) at Fraunhofer ISE. Results will include the solar thermal yield performance, the decrease in cavity temperature due to STVB heat absorption and transfer rates, the performance and reliability of the mechanism, and the performance of DSF with integrated STVB.
In both STVB operation scenarios "high solar thermal yield" and "low g-value" the STVB are expected to reduce the heat transfer from cavity to interior by lowering cavity temperature. The difference of the low g-value concept is a lower absorption of radiation and/or higher heat transfer rate. It will be used to reduce the cavity temperature even more. Thus enabling e.g. the usage of double insulated glazing within double skin facades instead of triple insulated glazing while at the same time reducing the interior surface temperature of the glass ideally to room temperature. Consequently the fluid temperature resulting from STVB will be lower as within the high solar thermal yield concept.

FIG. 11 Visual impression of DSF with integrated STVB (left) © IBK2. Current stage of LabTestSample (right) © Fraunhofer ISE

These results will be applied to future developments. At the time of writing, for example, the design based on the LabTestSample is overly complicated. The STVB slat, for instance, has 10 main components with multiple screws, which take approximately 30 minutes for two people to assemble. For comparison, a typical venetian blind slat can be produced at approximately 20 – 40 m^2 per hour (Dallan, 2013). The STVB assembly process hence needs to be simplified. To this end, STVB slats are currently being designed to be produced with extrusion, which can reduce the slat component to less than six elements with fewer manual fixings. This advance will optimize the assembly process, improve the structural properties of the slats, and reduce human error. An extrusion method could also be applied to the pressing mechanism, conferring similar advantages.

Acknowledgements

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Bio-inspired Transparent Microfluidic Platform as Transformable Networks for Solar Modulation

Abstract Only! Full Paper in JFDE 2019.1

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Abstract

The glazed envelopes on buildings play a major role in operational energy consumption as they define the boundary conditions between climate and thermal comfort. Such a facade is viewed as an uncontrolled load that sets the operational performance requirements for artificial lighting and air-cooling mechanical systems. This is in contrast to nature, which has evolved materials with the ability to learn and adapt to a micro-environment through selfregulation using materials that are multifunctional, formed by chemical composition in response to solar load. Leaf vasculature formations are of particular interest to this paper. Through leaf maximisation of daylight capture, the total leaf area density and angular distribution of leaf surfaces define the tree structure.

This paper will define an approach to simulate nature to advance a microfluidic platform as a dynamic NIR absorber for solar modulation: a transformable network of multi-microchannel geometry matrix structures for autonomous transparent surfaces, for real time flow management of conductivity. This is realised through active volumetric flows within a capillary network of circulation fluidics within it, through it, and out of it for energy capture and storage, the cycle of which is determined through precise management of heat flow transport within a material. This advances transparent facades into an energy system for heat load modulation nested to climate and solar exposure, which is demonstrated in this paper.

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PART 3 // ENERGY

Three Case Studies of a Prefabricated Window Element for Refurbishments

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Abstract

Almost 40% of energy consumption in Germany is used in the building sector. The largest part of the building stock was built between 1949 and 1979 and performs the worst in terms of energy efficiency. Our research project seeks to discover how as many requirements as possible can be incorporated into a functionally expanded prefabricated window element for use in the energy-saving renovation works of post-war buildings. The installation of conventional window replacements is complicated by the involvement of many trades and numerous interfaces at geometrically and structurally challenging places. Through the integration of sun, glare and insect protection in an elegant, prefabricated, quality element – the "window machine" – residents should profit from a less intrusive construction process, lower capital costs as well as higher energy efficiency. Alongside typical window functionality, the inclusion of building services such as ventilation / heat exchanger, electrification / building automation were studied as additional components in the window element. The many potential solutions identified at the start of the project were further investigated according to the following parameters: Design quality, modular construction, simplified construction process, maintenance and dismantling, reduction of interfaces and associated trades, integration of functions, degree of tolerance, connection to surrounding building elements, daylight, sun protection, insect protection, heat protection and isothermal characteristics. The advantages and disadvantages of each construction were compared and analyzed. Proposals were developed over several selection rounds resulting in three prototype case studies. Meanwhile, three proposals for integrated ventilation were chosen and assigned to the prototypes. In accordance with idea of prefabrication, the window is conceived as an inte¬gral component of the element. Following the same principles as a car production series, the form is governed by the installation of the maximum range of features, with individual components incorporated as desired in a given project. The simplification and speeding up of the construction process requires a precise building survey and more in-depth planning. Thus, the focus of effort shifts from the construction itself to the planning and production processes. Prefabrication offers new possibilities in the reduction of different materials and their correct separation for recycling (recyclability). The economic and energy efficiency of the window module is a function of the technologies integrated: The greater the number of services accommodated in the window element, the more worthwhile the additional expense as compared to a conventional window replacement. In addition, energy savings are achieved through the thermal insulation and heat recovery from the ventilation system.

Keywords

refurbishment, window replacement, prefabricated element, ventilation, shading system

6 INTRODUCTION

6.1 SUBJECT AND BASIC ASSUMPTIONS

The building sector accounts for nearly 40% of energy consumption in Germany (Bundesverband der Deutschen Industrie eV, 2013). While consumption in the new building sector has dropped continuously since the introduction of the first Thermal Insulation Ordinance (Bundesregierung, 1977) in 1977 and EnEV (Bundesregierung, 2001) in 2002, considerable efforts are still required to reduce energy consumption in existing buildings. The vast majority of these buildings date from the period before 1977. Of these, residential buildings constructed between 1949 and 1979, which constitute more than a third of all existing buildings, perform worst in terms of energy demand. To achieve the federal government's climate protection goals (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2014), the energy-oriented refurbishment of these buildings is of the utmost importance. However, according to the BMWi – Federal Ministry for Economic Affairs and Energy (BMWi, 2014), the rate of refurbishment activities for building envelopes is currently just under 1 percent per year. Since the energy-oriented refurbishment of a building envelope is often only economically viable in connection with renovations which were pending anyway, additional incentives (BBSR, 2015) are required and obstacles to undertaking renovations must be removed (BBSR, 2016).

6.2 ENERGY RENOVATION PROBLEMS

While outer wall constructions and thermally insulated glazing now exhibit a high level of quality and are fully developed from an energy standpoint, many problems arise between windows and walls in terms of design, construction, building physics, functionality and organisation. The construction process for conventional window replacement is complicated by the coordination between the works involved on site which pose particular challenges in terms of geometry and building physics. As a result, "complaints about window connections to the building structure are one of the most common aspects of legal confrontations in the construction field." (Stiell, 2009). Window replacement is preferably carried out in warmer seasons (Lass & Benitz-Wildenburg, 2004) in order to guarantee the required minimum temperatures for processing the materials and to prevent the properties from excessive cooling. Protracted renovation activities on the other hand, particularly in warm seasons, represent a significant burden for residents who want to open their windows and do not want to live behind scaffolding for long periods of time. The inevitable conflicts with tenants deter many building owners from carrying out necessary or beneficial renovation work (BBSR, 2015).

6.3 OBJECTIVE

Efficient construction processes, work quality, delays in on site works and cost increases all provide motivation for this research project aimed at developing a prototype of a prefabricated window element with integrated technology for energy-oriented refurbishments. The term “window machine” addresses the integration of mechanical parts in the window and the connection with industry (prefabrication constructional process). The project focuses on the following points:

- Poor quality, time delays and cost increases should be reduced by minimizing the on site works involved;
- The highest possible degree of prefabrication;

- Minimization of problems between windows and walls related to building physics, design, construction, functionality and organization;
- Use of window machines during the energy-oriented refurbishment of the building envelope while flats are occupied.

7 METHODOLOGY

7.1 ASSESSMENT CRITERIA

In the first stage, relevant assessment criteria were identified and defined based on an analysis of the literature. The main assessment criteria were:

- Simplified construction process (professional, serially produced solutions);
- Modularity (building-block approach as development of individual modules which are implemented based on individual requirements and can also be retrofitted if needed);
- Window installation in the insulated base (the refurbished window is placed externally in the new insulated base in front of the existing wall. Tenants must be able to remain in their apartment during energy renovation and all construction work should be made from outside);
- Daylight (due to the negative mental impacts of artificial light for people (Department of Psychiatry and Psychotherapy, 2012), natural daylight is a requirement. Window openings should not be smaller after energy renovation.);
- Sun protection (due to increasing requirements for protection against summer overheating as a result of climate change and increasing demands in comfort, sun protection is necessary (Bundesverband Sonnenschutztechnik, 2017). The sun protection system of the window machine should require little space.);
- Mechanical ventilation (development towards increasingly improved insulation and thicker building envelopes, combined with the requirement to reduce ventilation heat loss requires controlled, user-dependent ventilation with heat recovery (Hausladen, de Saldanha, Liedl, & Sager, 2004). The ventilation system in the window machine should be fully or partly integrated in the insulated base);
- Installations transfer to the exterior (cable routing of building service equipment on the outer side of the exterior wall opens up new possibilities);
- Assembly (larger elements are either "threaded in" from above in the gap between the scaffolding and the building, or - without scaffolding - installed using a cherry picker. The window machine should have a low weight for easy installation.);
- Life cycle/ recycling (assuming an average life cycle of ca. 40 to 50 years (Kehrer, 2017) and depending on the building condition and material composition of the exterior wall, it may be beneficial, to incorporate the next window replacement into the planned works);
- Installation and material cost of the window machine (it should be installed by a single company and not by a number of tradesmen. This would save overall costs and improve quality compared to conventional window replacement. The window machine should be compact and resource-efficient).

7.2 CASE STUDIES

The second stage focused on developing the prototype, based on the principle of the window frame: an outer component into which a composite unit of window and building technology will be integrated. The four basic components (a window frame, a sun protection system, a ventilation system and a window) were arranged in twelve different combinations (case studies). The aim was to gain knowledge about the interaction of all basic components. Each project partner rated each case study (see Tab. 1) according to the assessment criteria (A stands for good, B for neutral and C for bad).

At the end, the grades were summed and the three cases with the highest "well-valued" sum were further discussed with the project partners. It was decided to work on the three different cases (outward opening window, window casings, integrated window) in order to prove the advantages of installation, cost and design. In the next stage three cases were compared in a simulation in terms of building physics, daylight, installation and cost.

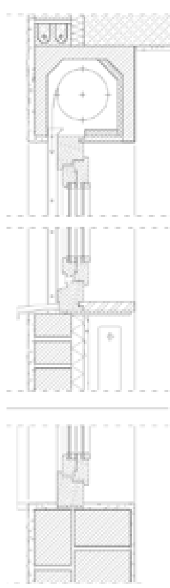
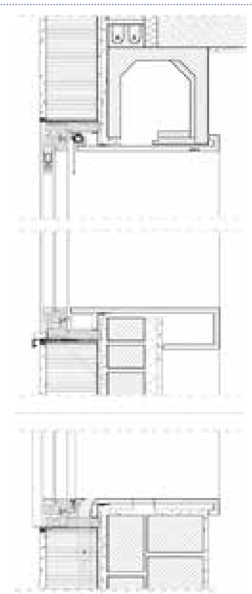
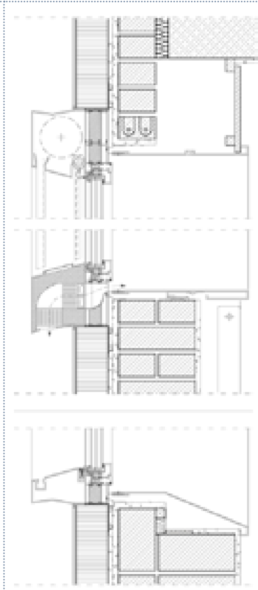
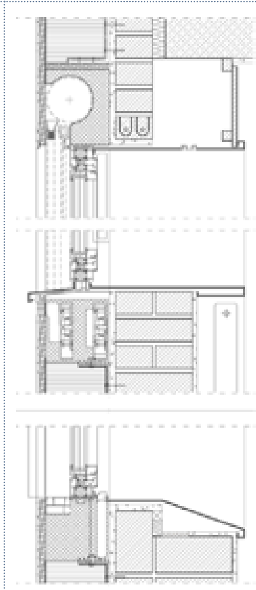
EXISTING CONSTRUCTION	CASE 1: Outward opening window	CASE 2: The comeback of window casings	CASE 3: External Thermal Insulation Composite System (ETICS) - integrated window
Existing buildings from the 1950s to the 1970s (Federal Ministry of Transport, Building and Urban Development, 2009).	Approximately 30% more glass area compared to the existing window.	Decentralized ventilation unit is a modification of the industrial unit's ventilation unit.	The new element with all technical components in the insulation layer.
The existing constructions comprise 25-cm-deep lintels flush with the reinforced concrete ceiling (200 mm WLS 2.3 W/m*K).	The supply and exhaust air connections are provided for airing the rooms via ventilation ducts in the insulation level.	No drilling in building substance (ventilation).	The newly developed decentralized ventilation unit.
	The window frame is from inside invisible.	Maintenance work is carried out from the outside.	Completely prefabricated as a built-in element delivered to the construction site.
The only existing insulation (WLG 040 with 40 mm) is in the area between the reinforced concrete ceiling and the brick lintel.	Advantages: gain in daylight, fewer components, weather resistance Disadvantages: Cleaning, external sun protection not possible	Advantages: flexibility in the integration of the technical components, variations in the design, cleaning, reuse Disadvantages: maintainance	Advantages: completely prefabricated, completely integrable element, light, cleaning Disadvantages: the decentralized system not easy to maintain
			

TABLE 3 Existing constructions and development of the three models *(Drawing: EBB, TUM)*

8 EXPERIMENT / RESEARCH

8.1 EXAMINATION OF BUILDING PHYSICS

To ensure the comparability of the cases examined in the research study, identical building materials and component dimensions were used (for the most part) as a basis for component geometry and implemented materials, both for the existing model and the study cases (see Tab. 2). However, there were deviations in the structural thickness of the ETICS (External Thermal Insulation Composite System). The different cases were assessed according to the following examination criteria using a two-dimensional thermal bridge analysis (Software Therm 7.3):

- Minimum inner surface temperatures at the critical points;
- Heat flow in the component;
- Thermal bridge coefficients (ψ values);
- Risk of mould;
- Dewpoint limit

Two-dimensional thermal bridge analysis is the standard (DIN 4108-2:2013-02, 2010) accepted method for minimising moisture damage and investigating the risk of mould. The minimum inner surface temperature should not fall below 12.6°C. For windows (glazing and frame), the tested critical surface temperature is 9.3°C.

COMPONENT	EXISTING CONSTRUCTION	CASE 1	CASE 2	CASE 3
Window	Double glazed window (Uw = 2.6 W/m²*K)	"Fenestra Top Wing", triple-glazed window (Uw = 0.91 W/m²*K)	"Heroal W72", triple-glazed window (Uw = 0.84 W/m²*K)	"Heroal W72", triple-glazed window (Uw = 0.84 W/m²*K)
Thermal insulation	None	16-cm-thick ETICS (External Thermal Insulation Composite System) (0.35 W/m*K)	16-cm-thick ETICS system (0.35 W/m*K)	16-cm-thick ETIC system (0.35 W/m*K)

TABLE 4 Boundary conditions for the different variations in the examination of building physics

8.2 DAYLIGHT PERFORMANCE

Using the simulation tool Simulationstool Fener, the three cases were compared with the existing construction. The same building structure opening dimensions were used as a basis for the existing window model in all three cases.

Boundary conditions:

- Weather file: Frankfurt/Main (Meteonorm).
- Room geometry: 4.00 x 4.34 x 2.50 m
- Window opening: 2 windows each 1.23 x 1.48 m
- Window direction: South
- Wall thickness: 30 cm
- Insulation thickness: 16 cm (0 cm for the existing model simulation)

8.3 INSTALLATION AND COST

The window machine should build on the principle of the window frame (Baldenhofer, 1989), a surrounding component into which a window is integrated. The systems integrated into the window machine, insofar as they are subject to mechanical stress, should allow for inspection either by removing the window (from the outside) or by removing the inner lining. To minimise disruption for the user, the window casements should be mounted directly after removing the old blind frame. This construction method and the highest possible degree of prefabrication should reduce the onsite works and involvement of many trades. With only one responsible trade, the problems between windows and walls related to building physics, design, construction, functionality, organization and cost should be minimized. By integrating building technology in a prefabricated quality element, the user should also profit from lower costs in renovation projects.

9 RESULTS

The basic question is whether a high-tech prefabricated solution or conventional window change at energy renovations is more advantageous in terms of the consumption of energy, materials, time and money. In order to answer that question, this research compared the advantages and disadvantages of three cases (examination of buildings physics, daylight performance, installation and cost) with the conditions in the existing constructions from the 1950s to the 1970s.

9.1 EXAMINATION OF BUILDING PHYSICS

Tab. 2 shows the thermal performance results (heat flow and temperature progression) of the investigated window machine cases. The temperature progression indicates temperatures in the component (low temperature -5°C = purple, high temperature 20°C=red). As expected, the existing construction exhibited the highest thermal losses (low temperatures in the component). The points at which the lowest surface temperatures are generated, and which exhibit different temperature progressions in each of the cases, are referred to as critical points (see the black points in the temperature progression column in Tab. 3). The differences between the cases are slight and Case 3 (element fully integrated into the insulation layer) has the lowest thermal losses (high temperatures in the component).

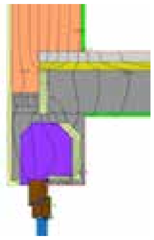
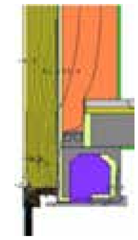
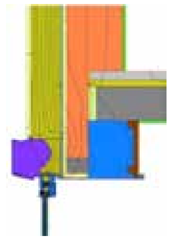
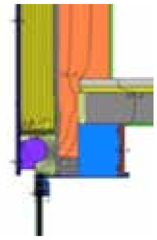
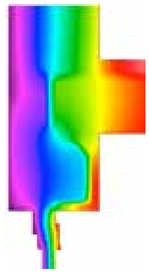
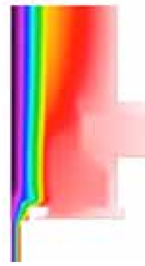
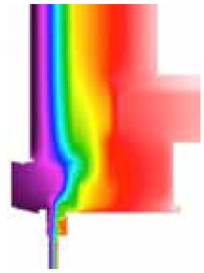
NAME	EXISTING CONSTRUCTION	CASE 1	CASE 2	CASE 3
Heat flow in the component				
Temperature progression				

TABLE 5 Heat flow and temperature progression for the different cases. Drawing: Beck+Heun GmbH

9.2 DAYLIGHT PERFORMANCE

As expected, Case 1 delivers the best results both with respect to daylight (76,43% of daylight autonomy) and in terms of solar gain (60,72 kWh/m2). For daylight autonomy, the differences between the three cases are very slight, with the insulation thickness being the most important factor for this aspect. For solar gain, the size and position of the window panes are the decisive factors (see Tab. 4).

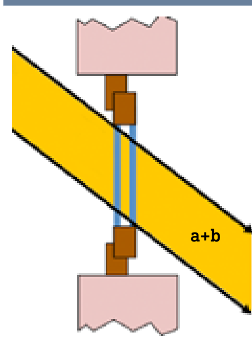
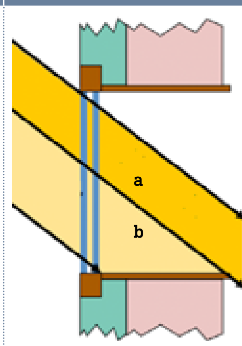
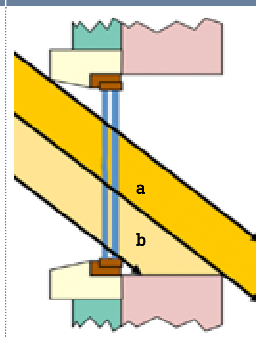
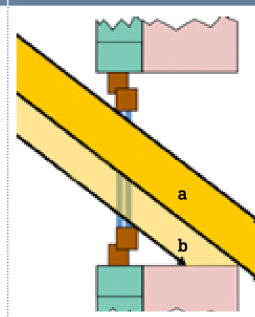
EXISTING CONSTRUCTION	CASE 1	CASE 2	CASE 3
			
a (daylight autonomy) 73,56 % **b** (annual solar radiation) 36,67 kWh/m2	**a** (daylight autonomy) 76,43 % **b** (annual solar radiation) 60,72 kWh/m2	**a** (daylight autonomy) 74,49 % **b** (annual solar radiation) 42,70 kWh/m2	**a** (daylight autonomy) 74,08 % **b** (annual solar radiation) 46,27 kWh/m2

TABLE 6 Daylight and solar energy generation. Drawing: Fraunhofer Institute for Solar Energy Systems ISE

9.3 INSTALLATION AND COST

In this section, the installation of three cases is described. There is a small difference between the installation processes of the three cases (see Tab. 5). In the first stage, an installation frame was mounted on the exterior wall. After this, the window element itself (partially or fully, depending on the study case) and exterior wall insulation (ETICS or rainscreen) were installed. In the last stage, the existing window was removed, the sidewalls of the opening were covered with an inner frame and technical units (ventilation system and sun shading system) were connected to the electricity supply. It was calculated that the window machines were to be completely assembled in only two days due to the decreased number of trades involved, and installed by a single company. Next to minimising the number of trades, the installation also addressed the use of material. Case 3 for example has the advantage of easy handling thanks to the light weight of the insulation module and the fact that it could be installed using a cherry picker or two workers. Larger elements could be "threaded in" from above, in the gap between the scaffolding and the building. Regarding ventilation systems, Case 1 includes central mechanical ventilation integrated into the exterior wall whereas Case 2 and Case 3 use decentralized systems integrated into window element itself. To this end, the decentralized solution was more accessible for fast installation, easy maintenance and further upgrading of technology. The comparison of the cases shows that the Case 3 is the best scenario for low occupant disturbance, fast construction works and ease of maintenance.

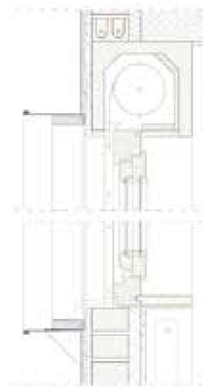
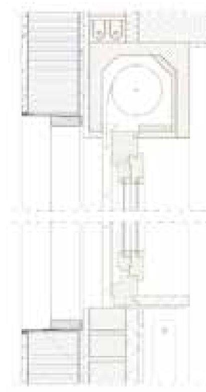
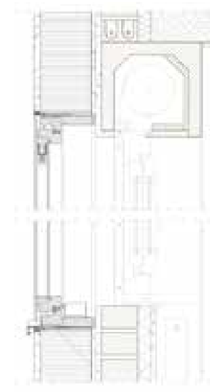
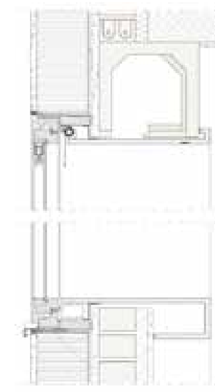
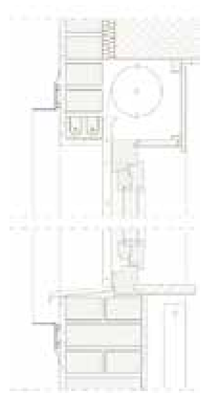
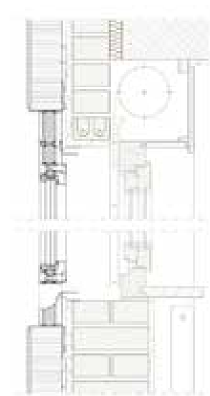
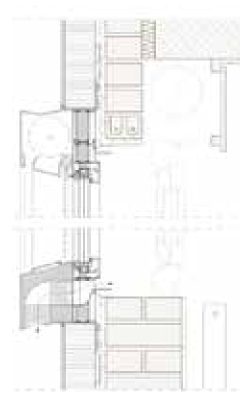
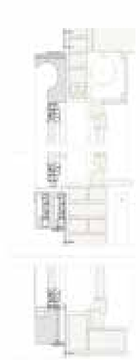
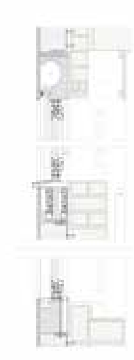
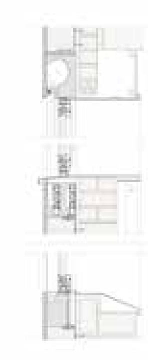
NAME	STEP 1	STEP 2	STEP 3	STEP 4
Case 1				
	Application of the assembly sub-frame to the exterior wall	Assembly of exterior wall insulation and covering	Installation of window element and removal of existing window	Installation of cover for interior opening
Case 2				
	Installation of the pre-assembled connection bracket adjusted to the window size, and preparation of seal with building envelope	Installation of the window element, exterior wall insulation and covering	Installation of technical elements and removal of existing window	Installation of cover for interior opening
Case 3				
	Installation of the completely pre-assembled window element and seal with the building envelope	Integration of sun protection and insect protection, preparation of ETICS system	Removal of existing window	Installation of cover for interior opening

TABLE 7 Installation of Case 1, Case 2 and Case 3. Drawing: Chair of Building Construction and Building Material Science, TUM

In the last stage, the cost planning of the construction process was considered. There were no big differences between the study cases. The cost included material cost (window machine production, construction, façade insulation, ventilation units, shading units), works on the building site (preparation, installation, removal of the existing components) and transport costs. A comparison between the window machine and conventional window replacement made clear, that the window machine requires extensive preparation in precise building surveys and in-depth planning. Once planned, however, the window machine could be completely assembled in two days and saved approximately 10% overall costs compared to conventional window replacement. In addition, design defects were also reduced.

9.4 DISCUSSION AND OUTLOOK

The construction process for conventional window replacement is complicated by the many different works involved on site and the need for considerable coordination where there are particular challenges in terms of geometry and building physics. In developing the three window machine case studies for energy-related refurbishment, their performance was compared in terms of daylight, building physics and ease of installation considerations.

The outward-opening window in Case 1 allows for a significant gain in daylight and an entirely new room ambience. The weather resistance of the glass is a positive factor, as is the reduction of components, in particular the behaviour of different materials applied together (for instance, in the case of temperature fluctuations). The wraparound trim in Case 2 offers lots of design flexibility for integrating additional components, also with a view to future adaptability. Case 3 benefits in terms of handling from the low weight of the insulation module. The element is delivered as a fully prefabricated component to the construction site, so only the inner frame needs to be installed.

The research shows that all window systems speed up construction processes, minimize the cost and avoid defects between windows and walls at energy-oriented renovation works. Importantly, the essentially undisturbed occupation of the flats is possible when using window machines as part of the energy-oriented refurbishment of the building envelope.

10 CONCLUSIONS

The window machine is assembled by a single company and saves cleaning work, painting work, sun protection work and the coordination of these tasks on site in the window area. With respect to the reduction in the variety of installed materials, separation according to type (recyclability), improved performance in terms of light and building physics, the window machine opens up new possibilities for energy-oriented refurbishments. Three case studies were developed and compared in a simulation in terms of installation, daylight and building physics. The results were strongly influenced by the industrial partners' technologies. Therefore, it would be necessary to also verify different technologies and construction materials. The third case study was further developed, optimised and implemented in a demonstration project in a subsequent phase of the research study, as a result of the feasibility criteria of the industrial partner's technologies.

Acknowledgements

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Fluidglass – The Energy Efficient Glass Façade

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Abstract

Transparent glass façade elements with inner circulating fluids - so-called Fluidglass – consist of an insulating glazing unit with two additional glass panes, one on the outside and the other one on the inside. The two additional window pane gaps are filled with fluids, which are connected to fluid circuits. This Fluidglass circuits are connected to the regular building services circuit via heat exchangers. Fluidglass combines the following functions in one transparent façade element: adaptive glazing, with thermal insulation and variable sun and glare protection, flat heating and cooling system and solar collector.

Using the developed simulation models that have been validated with results from experimental studies, parameters of the Fluidglass functions were calculated.

As adaptive glazing, Fluidglass controls the transmission of solar radiation into the interior. With a 2 mm thick fluid layer, by switching from clear to colored state, visual transmission is reduced from approx. 70% to 7% and solar transmission from approx. 45% to 5%. By enlarging the fluid layer up to 6 mm, solar and visual transmission can be completely eliminated. Thus, Fluidglass has excellent properties as adaptive glazing.

As a solar collector, Fluidglass has a low efficiency. Nevertheless, up to approx. 85% of shortwave solar radiation impacting on the façade can be absorbed within the fluid circuit and partly dissipated as thermal heat gains. Fluidglass can thus utilize the waste heat as a regenerative energy source e.g. for domestic hot water preparation. This is an advantage over other sun protection systems.

By implementing the model in dynamic-thermal building simulations, the applicability of Fluidglass façades in fully glazed administration buildings is examined at three climatically different locations: cold, temperate and hot, represented by Moscow, Munich and Riyadh.

At all three locations, an office space with Fluidglass façade has low energy requirements, the thermal and visual comfort is good or very good and the thermal energy gains are up to seven times higher than the energy demand of the office space.

Fluidglass offers the potential to turn buildings with a large proportion of glazing from buildings with high heating and cooling demand into energy-efficient buildings whose façades also enables the use of local, renewable energy sources.

Keywords

glass facade, adaptive glazing, solar thermal, energy harvesting, heating and cooling system, sun protection, glare protection, thermal comfort, energy efficiency, building simulation

1 INTRODUCTION

The building sector plays a key role in the energy concept of the European Union with about 40% of final energy consumption and about 36% of greenhouse gas emissions. The concept provides for a drastic reduction of primary energy demand and greenhouse gas emissions in order to limit global warming below 2° C (Groezinger et al., 2014). From 2020, all new buildings in the EU will be implemented as nearly Zero Energy Buildings (nZEB). These buildings should have nearly no energy demand and cover the remaining demand for a high proportion from renewable energy sources on site or nearby (Comission Recommendation (EU) 2016/1318, 2016).

Buildings with a large proportion of glass surface, in particular administrative buildings with year-round high internal loads, pose particular challenges. At low outside temperatures they have high transmission heat losses and thus a high heating demand. With high solar irradiation, there is a risk of overheating, especially in tall buildings without external sun protection. The energy demand for cooling increases due to the solar gains, in addition to the internal loads. Besides the high energy requirements, the thermal comfort of these buildings is usually difficult to maintain. On the other hand, glass facades offer the opportunity of using solar energy and daylight in the building. This saves energy for heating, domestic hot water and artificial lighting.

The idea of the Fluidglass façade is to turn hitherto inefficient glass high-rise buildings into nZEBs. The Fluidglass is designed to control the energy transmission between the exterior and interior space within the façade and to harness the renewable solar radiation over the entire façade surface (Stopper, Ritter, & Gstoehl, 2014).

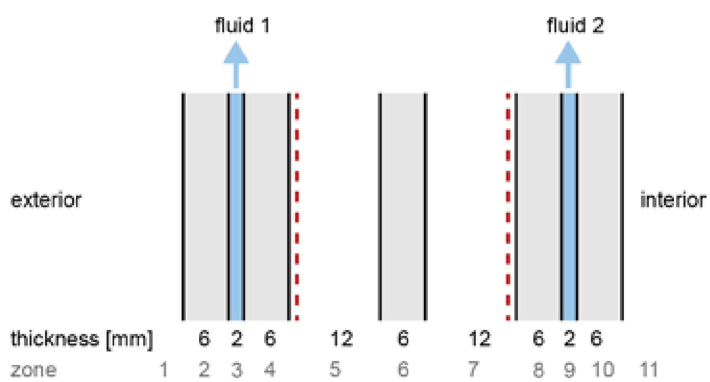


FIG. 12 Structure of the Fluidglass element

Fluidglass is a transparent glass façade element with inner circulating fluids. As shown in Fig. 1, it consists of an insulating glazing unit (zone 4 to 8, with two low-e-coatings and krypton) with two additional glass panes, one on the outside (zone 2) and the other one on the inside (zone 10). The two additional window pane gaps are filled with fluids (zones 3 and 9), which are connected to a fluid circuit. These Fluidglass circuits are connected to the regular building service circuit via heat exchangers (see Fig. 2).

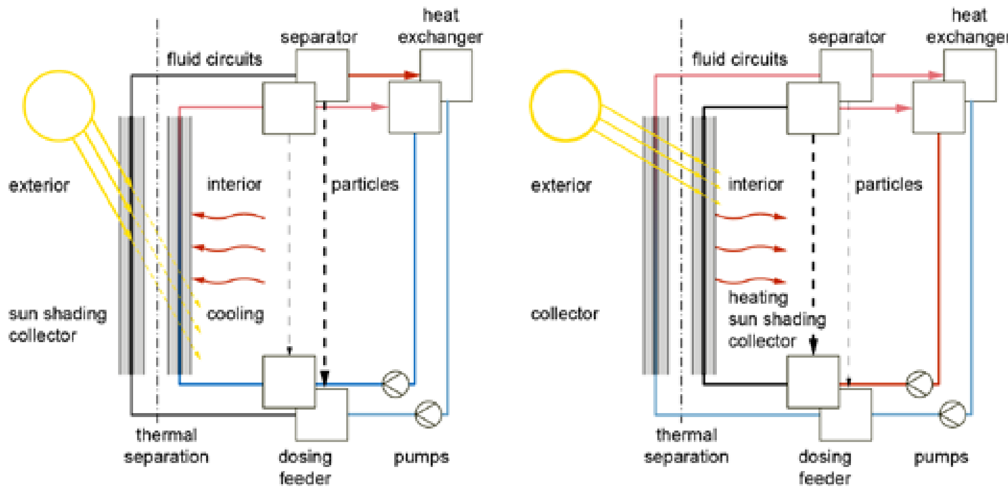


FIG. 13 Fluidglass concept in the cooling (left) or heating period (right)

Fluidglass combines the following functions in one transparent façade element:

- adaptive glazing, with thermal insulation and variable sun and glare protection
- flat heating and cooling system
- solar collector

The Fluidglass can be installed in standard glass façade profiles. Compared with other glass facades which integrates sun shading protection and waste heat utilization, e.g. double facades systems, the Fluidglass is very slim with about 6 cm depth. This allows a maximum space utilization.

In order to increase the absorption of the solar radiation within the Fluidglass, the inner and outer fluid can be reversibly dyed with iron oxide nanoparticles. They can be removed by means of a magnet with low energy consumption (see Fig. 3)

FIG. 14 Process of discoloration by means of a magnet

Even with a high color concentration within the fluid, a distortion-free view through the Fluidglass is always given (see Fig. 4). For this reason, the façade can be completely equipped with fluid glass.

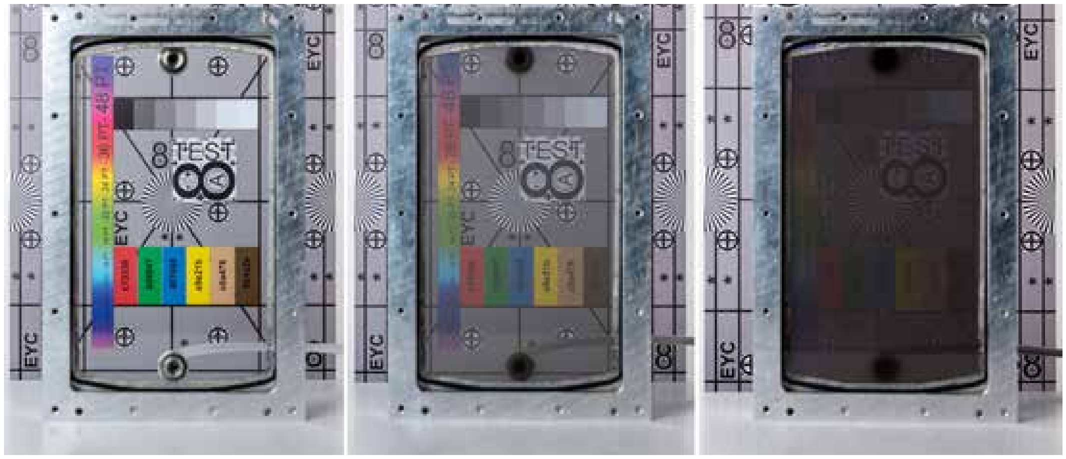


FIG. 15 Fluidglass prototype with clear fluid (left) and increasing color concentration (from middle to right)

2 METHODOLOGY

The Fluidglass was modeled in the software EES ("Engineering Equation Solver (EES)") and validated with measurement results from experimental studies. In EES, characteristic values of the Fluidglass elements were calculated. For the dynamic-thermal building simulations, the model was transferred to the software SimulationX ("SimulationX 3.6") and validated with further measurement results and building simulations within the European Research Project "FLUIDGLASS" [1] (Baumgärtner, Krasovsky, Stopper, & Grabe, 2017). For the annual simulations, a simplified, sequential control strategy was implemented to control the coloring, the inlet temperatures and the mass flows of the two fluid circuits. In a first step, the control strategy regulates the coloring concentration of the fluid to a target illuminance level between 300 and 4000 lux at working level. During the heating period, the inner fluid is colored in order to utilize the solar gains in the interior space with low losses to the outside. In the cooling period, the outer fluid is colored to avoid overheating of the office space. In a second step, the flow temperature of the internal fluid is controlled. The interior space will be either heated with an inlet temperature of maximum 35° C or cooled with a minimum fluid temperature of 18° C. The control strategy optimizes the operative room temperature to fulfill comfort category A based on ISO 7730 (ISO/TC 159/SC 5, 2005). For the building simulations, a standard single office room with nearly 100% Fluidglass façade (dimensions: height 3.0 m, width 3.5 m and depth 5 m) was simulated (see Fig. 5). The performance of Fluidglass façades was examined at three climatically different locations: cold, temperate and hot, represented by Moscow, Munich and Riyadh. At all locations, three different orientations were simulated – north, south and west.

The net energy demand and the solar collector gains were calculated for the single office space as shown in Fig. 6.

Both the energy demand for heating, cooling and artificial lighting and the energy gains from the Fluidglass façade are converted to one square meter floor space.

1 The project was funded by the European Union within the European Union's Seventh Programme for research, technological development and demonstration (FP7/2007-2013), grant agreement No. 608509.

FIG. 16 Visualization of a fully glazed (Fluidglass without coloring) single office room in Munich

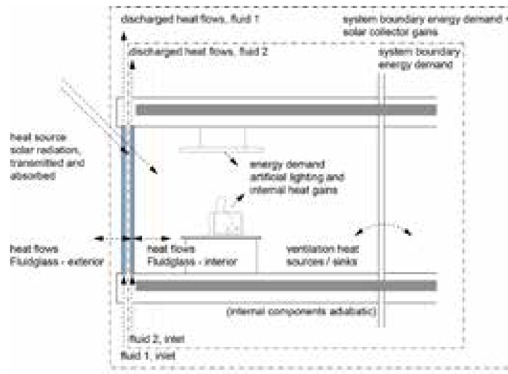


FIG. 17 Considered system boundaries for the net energy demand and the solar collector gains

3 RESULTS

3.1 CHARACTERISTICS

The Fluidglass structure as shown in Fig. 1, using low iron white glass, was calculated in order to receive the following characteristic values: visual transmission (Tvis), solar transmission (Tsol), solar absorption (abs_total), Solar Heat Gain Coefficient (SHGC) and the overall heat transfer coefficient (U-value) (see Tab. 1).

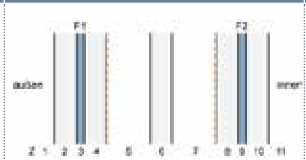
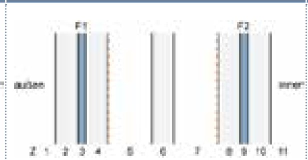
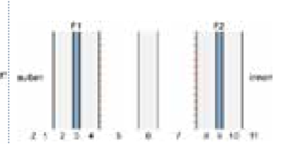
	FLUIDGLASS CLEAR	FLUIDGLASS – FLUID 1 COLORED	FLUIDGLASS – FLUID 2 COLORED
			
Tvis	0.70	0.07	0.07
Tsol	0.45	0.05	0.05
abs_total	0.33	0.90	0.74
SHGC	0.51	0.07	0.50
U-value [W/m²K]	0.43	0.43	0.43

TABLE 1 Characteristic values of Fluidglass, calculated in EES

Due to the low iron white glass, the visual and solar transmission of the Fluidglass with clear fluid is very high. The values are nearly as good as the integrated triple glazing. Because of the similar refractive indices of water and glass, the reflections on the glass surfaces adjacent to the fluid flown gaps are negligible. The two additional glasses are thereby almost neutralized. By coloring the fluid, the solar and visual transmission can be dramatically reduced from 70 % to 7% respectively from 45 % to 5%. The SHGC can be also switched from 0.51 to 0.07 by coloring the outer fluid [2]. Coloring

2 The visual and solar transmission could be totally blocked (Tvis = 0; Tsol = 0) by increasing the thickness of the fluid layer up to 6 mm. In order to avoid an additional inner glare protection, the visual transmissions of the Fluidglass needs to be lower than 5%.

the inner fluid, the SHGC remains as high as the clear state. Therefore the solar gains can be used during heating period while at the same time the visual transmission is reduce as glare protection. Fluidglass has excellent properties as adaptive glazing. It is comparable to other systems on the market, e.g. electrochromic glazing (Tvis ≈ 0.54 – 0.01; g-value ≈ 0.36 – 0.03).

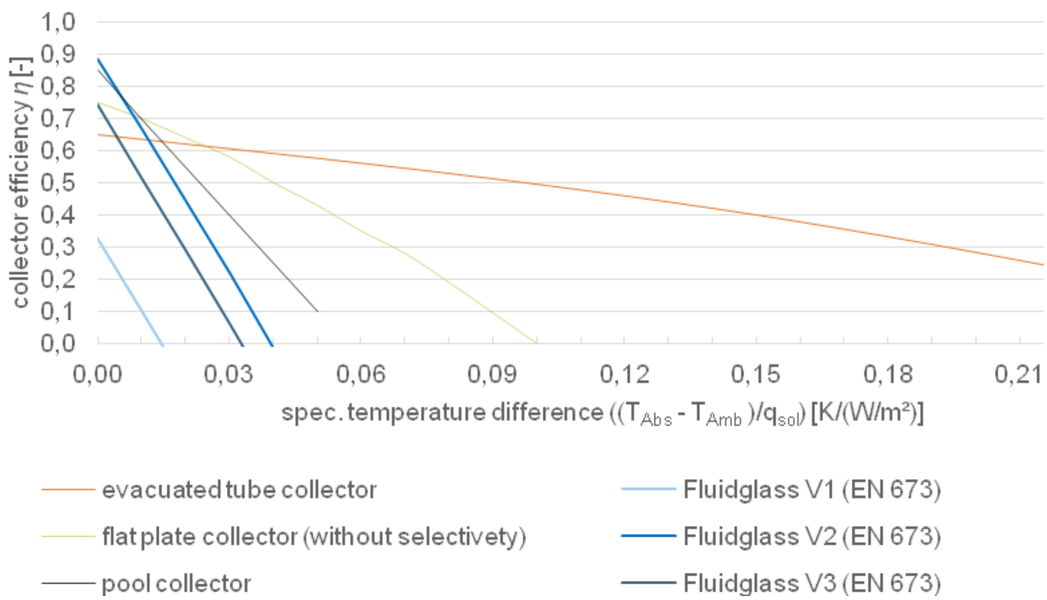


FIG. 18 Frequency distribution of the thermal comfort ranges within heating and cooling period; period of use; Moscow, north, south and west orientation

The optical collector efficiency[3] of Fluidglass with maximum color concentration in the exterior fluid (V2) is approximately 90 %, as shown in Fig. 7. This is within the very good range of a pool collector. By coloring the inner fluid to the maximum concentration (V3), the optical collector efficiency drops to 70 %. Without any coloring (V1), it even drops to 30 %. As the temperature difference between fluid and external temperature increases, the efficiency decreases strongly in all cases. For this reason, the Fluidglass as solar collector should be operated with low outlet temperatures.

Fluidglass as a surface heating has a system specific heating capacity between 34 and 125 W/m^2 per facade area with an internal heat transfer coefficient between 7.3 and 8.5 W/m^2K.[4] As a cooling device, the inlet temperature of the inner fluid layer is limited to 18°C to prevent condensation. The cooling capacity is in between 34 to 60 W/m^2 with room temperatures between 23 and 26°C. The internal heat transfer coefficient is between 7.2 and 7.7 W/m^2K.

3.2 BUILDING SIMULATIONS, MOSCOW

As shown in Fig. 8, the Fluidglass façade provides a very good thermal comfort for a single office space in Moscow. With every orientation, the maximum comfort level A is maintained at least in 80% of the time of use. Within the heating period, the operative room temperature is occasionally slightly higher (comfort level B), within the cooling period, sometimes lower (comfort level B or C). This is due to the simplified control strategy, which would have to be optimized in further research. The heating

For this reason, the fluid layers should be at least 3 mm thick.
3 Without any temperature difference between the fluid and the ambient temperature.

and cooling load is sufficient to heat and cool a single office space in Moscow at any time. Identical results have emerged for the location Munich.

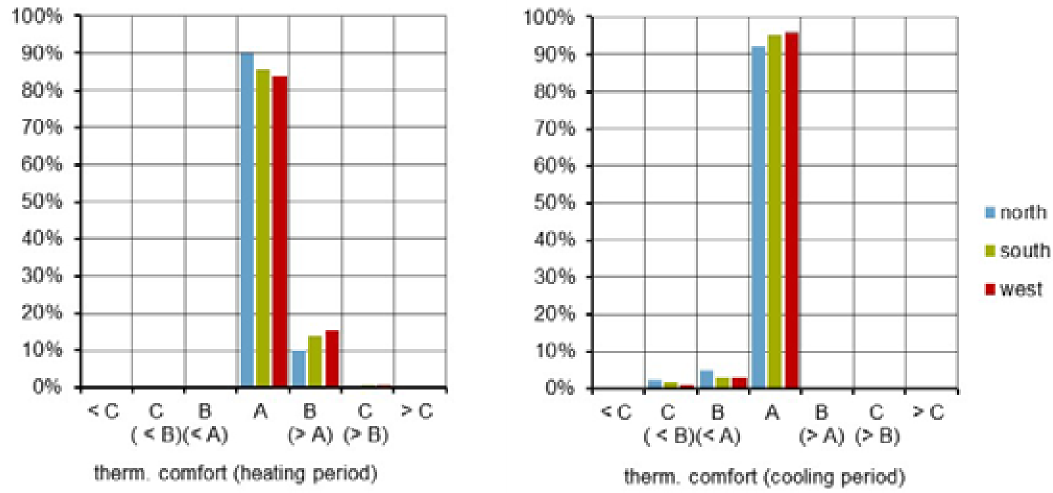


FIG. 19 Frequency distribution of the thermal comfort ranges within heating and cooling period; period of use; Moscow, north, south and west orientation

The energy demand for heating of a single office space, fully glazed with Fluidglass, is below 27 kWh/m²a at the north façade and below 22 kWh/m²a at all other orientations (see Fig. 8). Compared to typical heating demands of office spaces in Moscow – with approximately 40 to 60 kWh/m²a for heating (Hausladen, Liedl, & Saldanha, 2012) [3] Fluidglass façade qualifies office spaces in Moscow to be energy-efficient.

The solar thermal gains from Fluidglass exceeds significantly the energy demand in every orientation (see Fig. 8). The solar energy gains per square meter Fluidglass façade are in between approximately 140 kWh/m²a (north orientation) to 310 kWh/m²a (south orientation). It should be noted, that the maximum outlet temperatures are only 40° C. The most common temperatures for the outer fluid are between 20° C and 30° C (see also chapter 4).

4 The maximum specific heating capacity is calculated with 20°C room temperature and 35°C fluid temperature (f2). The minimum capacity is calculated with 25°C fluid temperature (f2).

5 According to Hausladen et al., the heating energy demand for energy efficient buildings can be reduced to 20 kWh/m²a with a glazing share of 50 %, cooling can be avoided. If the proportion of glazing is larger than 50 %, the heating demand increases for all orientations except for south orientation.

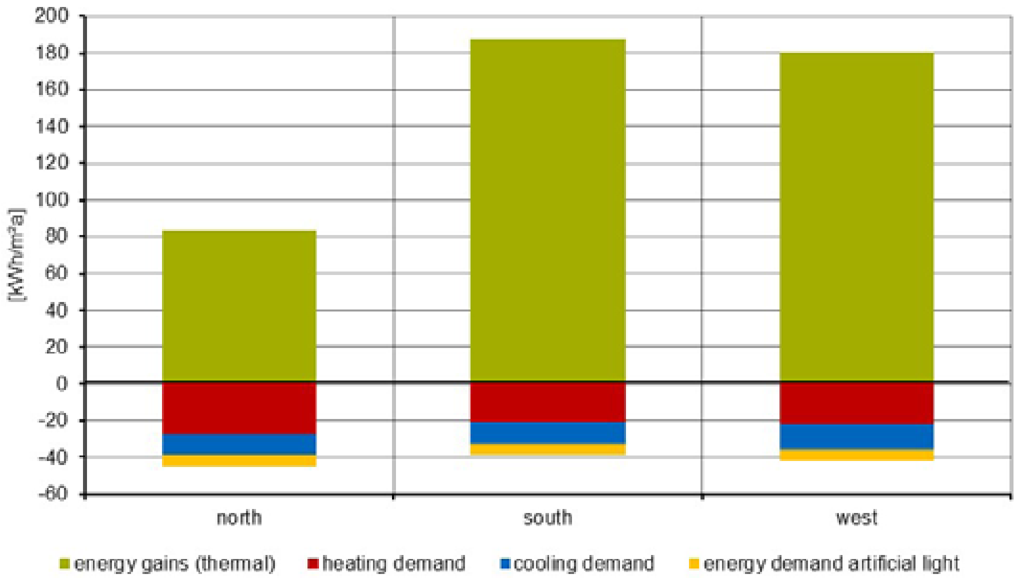


FIG. 20 Energy gains (thermal) and energy demand per usable area of a single office space; Moscow, north, south and west orientation

3.3 BUILDING SIMULATIONS, MUNICH

The results for thermal comfort in Munich are very similar to those in Moscow but even better. In every orientation comfort zone A will be reached in more than 90 % of the time of use.

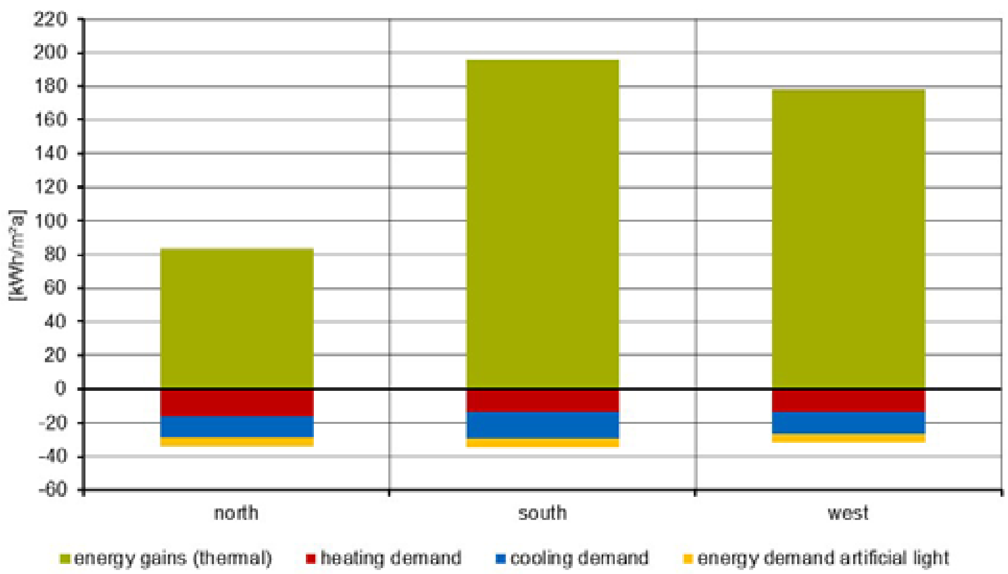


FIG. 21 Energy gains (thermal) and energy demand per usable area of a single office space; Munich, north, south and west orientation

Depending on the orientation, the specific annual heating demand is between 13 and 16 kWh/m^{2}a, and the cooling demand between 12 and 16 kWh/m^{2}a, as shown in Fig. 9. The energy requirement for artificial lighting in all orientations is approximately 5 kWh / m^{2}a. The heating energy demand corresponds with the "Passivhaus"-Standard [4]. This indicates a very energy-efficient office space in the Munich climate. As the inlet temperature of Fluidglass for cooling with 18°C is relatively high, cooling can be done energy-efficient, e.g. ground water cooling without any energy demand for cooling. As seen in Moscow, the thermal energy gains are exceeding the energy demand by far (see Fig. 9). The solar energy gains per square meter Fluidglass façade are in between approximately 140 kWh/m^{2}a (north orientation) to 320 kWh/m^{2}a (south orientation). However, the outlet temperatures are as well relatively low with a maximum of 40°C and the highest share between 20°C to 30°C (see also chapter 4).

3.4 BUILDING SIMULATIONS, RIYADH

In contrast to Moscow and Munich, the thermal comfort with Fluidglass façades are not as good in Riyadh (see Fig. 10). Especially in west orientation, 20 % of the period of use only comfort level C can be fulfilled. 3 % of the time, the operative room temperature exceeds 27°C. The cooling load of Fluidglass is not sufficient to guarantee maximum thermal comfort. If the user does not want to be limited, an additional cooling with low power would have to be provided.

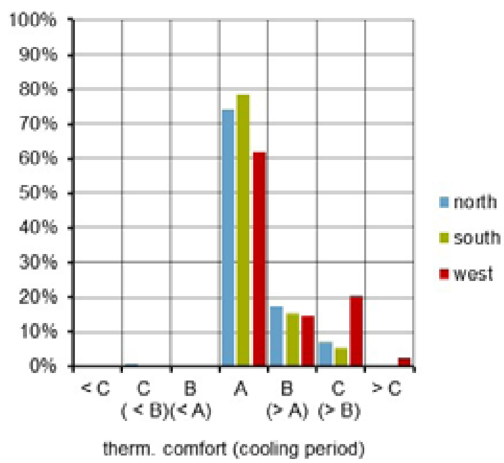


FIG. 22 Frequency distribution of the thermal comfort ranges within the cooling period; period of use; Riyadh, north, south and west orientation

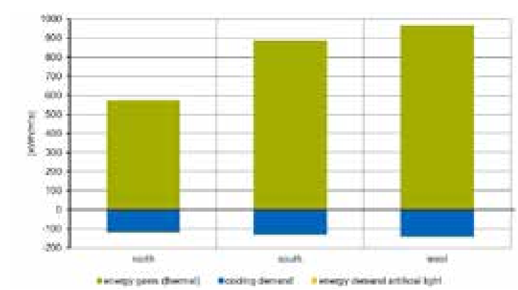


FIG. 23 Energy gains (thermal) and energy demand per usable area of a single office space; Riyadh, north, south and west orientation

The maximum cooling energy demand occurs in west orientation with 140 kWh/m^{2}K (see Fig.11). Compared to a typical cooling demand of an office space in Riyadh – with approximately 150 to 200 kWh/m^{2}a (Hausladen et al., 2012) – the Fluidglass façade enables the office space to be still energy-efficient also in Riyadh. However, the results are not as good as in cold and temperate climates, neither in terms of comfort nor energy requirements.

As in Moscow and Munich, the thermal energy gains exceeds the demand by far. The solar energy gains per square meter Fluidglass façade are in between approximately 1000 kWh/m^{2}a (north orientation) to 1600 kWh/m^{2}a (south orientation). The outlet temperatures of the external fluid are between 30 and 40°C (see also chapter 4).

6 Passivhaus upper limit for heating energy demand equals 15 kWh/m^{2}a.

4 CONCLUSIONS

Single office spaces with Fluidglass façade show very good thermal comfort in cold and temperate climate, represented by Moscow, Munich. In hot climate of Riyadh, the Fluidglass cooling load is not sufficient alone to reach maximum comfort level. However, the additional cooling load can be kept low. The building simulation results show relatively low energy demand for heating, cooling and artificial lighting at any of the three locations. Fluidglass office space can be called energy-efficient in the climate of Moscow, Munich and to a certain extent also in Riyadh. At the same time the thermal energy gains from Fluidglass are up to seven times higher than the energy demand of the single office space for heating, cooling and artificial lighting. Unfortunately the outlet temperatures of the Fluidglass as solar thermal collector are very low. Because of this, the solar thermal gains of the Fluidglass façade can neither directly be used for heating nor for cooling. For heating, it can be lifted up to 35° C, which could be efficiently done via heat pump, using the Fluidglass gains as natural source. For cooling purpose, the solar thermal gains of Fluidglass are useless. The temperature level is too low to be used for solar cooling via ab-/adsorption refrigeration machines. As the inlet temperature for the inner fluid layer needs to be minimum 18°C it would be ideal to use groundwater for cooling purposes. The thermal gains of the Fluidglass façade should be used as a natural heat source for domestic hot water, which is needed throughout the year. Via heat pump, the temperature level can be lifted up to 60°C, by having a very good efficiency. Since office building have no significantly domestic hot water demand, it would be preferable to use Fluidglass façade either for high rice buildings with residential or mixed use [5] or to provide the solar thermal gains via low-temperature heating network for residential buildings nearby (Baumgärtner et al., 2017). In any case, the thermal gains must be continue used, otherwise additional energy would have to be added to recool the fluid. That would turn the building's positive energy balance into a negative one.

As the electricity demand of buildings are key needs, e.g. for cooling, ventilation fans and plug loads, future investigations of Fluidglass facades should consider integration of photovoltaic cells. Especially in hot climates, the electricity could be used to operate the needed HVAC-Systems, as the Fluidglass hot water gains cannot be used for cooling. In addition, the required heat pumps – e.g. for domestic hot water - could be operated with the electricity gains in any climate zone. The implementation of Fluidglass facades is currently still in prototype status. There are still major challenges in terms of the technical implementation with regard to the reversible coloring and the spacers in the space between the panes. Apart from that, there will be also challenges in the building integration with the connection of the fluid circuits within the facade and the integration in the building automation. Supposing the problems could be solved, Fluidglass offers the potential to turn buildings with a large proportion of glazing from buildings with high heating and cooling demand into energy-efficient buildings whose façades also enables the use of local, renewable energy sources.

Acknowledgements

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7 E.g. Raffles City Hangzhou by UN Studio

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Active Moisture Control of Façades by Smart Ventilation System

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Abstract

Liquid water on surfaces of façades supports the growth of microorganisms like algae and fungi, leading to an aesthetical issue due to the discoloration of the façade. This subject became more significant with the increased spread of buildings equipped with external thermal insulation composite systems (ETICS). Nowadays, potentially environmentally harmful substances like biocides are used to hinder the growth of microorganisms, conventionally applied in the form of paints and need to be reapplied every 5 to 10 years.
This contribution presents an innovation that eliminates the need for anti-fungal and anti-algae chemical coatings in a sustainable way. An active moisture control system has been developed for enabling targeted drying areas of the façade. This system consists of a low-cost sensor network, data acquisition and smart processing technology, and a ventilation system. Using the data of the sensors and further parameters in the software controlling the ventilation unit, leads to an efficient system that allows to detect rain incidents and their end and therefore to a smart activation of the ventilation unit.
This results in a more sustainable solution compared to fungicide or algaecide paints, which typically need to be reapplied every 5 to 10 years to maintain their effectiveness, especially in wet climates.
In summary, we have developed a cost-efficient solution to keep the façades clean of microorganisms without the use of chemicals that potentially are harmful to the environment.

Keywords

microorganisms, ventilated façade, smart façade, sensor network, sustainability

1 INTRODUCTION

Microbiological growth on façades became an aesthetical issue, particularly as buildings are equipped with improved thermal insulation to reduce heat losses and therefore the environmental footprint (Barreira, 2013). As a consequence, surfaces of buildings are cooler and the surface temperatures fall below the dewpoint leading to condensation of water on the façade, one of the main necessities for microbiological growth. The result is a longer growth cycle of microorganisms for thermally insulated façades (Krus, 2006).

Usually biocides are added to exterior paint to hinder the spread of microorganisms on the façade. This concept for avoiding microorganisms has a limited durability by leaching of the additives caused by rain etc. (Bollmann, 2016), meaning that the finishing layer has to be renewed every 5 to 10 years. Furthermore these substances are potentially harmful to the environment and can persist for a very long time. Although only approved biocides are used and therefore the risk of harming the environment is minimized, this solution is not sustainable.

Water is the key factor for microorganisms to grow. A reasonable way to prevent that growth is to keep the surface of the façade as dry as possible. Some incidents like rain cannot be held away from the façade, without having strong impact on the design of the building (like the use of large roof overhangs). Another way to keep the surface dry is to suck the water in the façade by capillary effects. This means that water uptake in general is higher, and that the façade will need more time to dry, although the surface is apparently dry.

Another method to keep the overall water uptake low by the use of hydrophobic surfaces and still keeping the surface of the façade dry is to dry the surface by ventilated air. This method is further analyzed in this contribution as a sustainable method to prevent microbiological growth.

2 METHODOLOGY

The working principle of such a ventilation system for façades is shown in Fig. 1. The ventilation unit takes air from the front side of the façade and leads it along the façade from top to bottom through an air outlet on the lower side. The unit itself is integrated in the ETICS, as well as the sensors, for a minimum aesthetical impact on the façade.

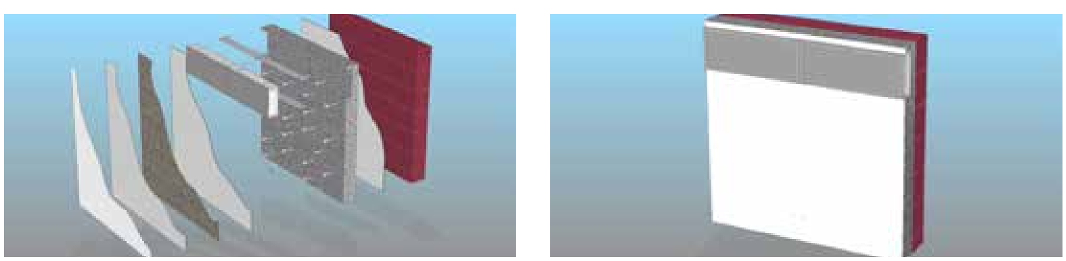

FIG. 1 Scheme of a ventilated façade

First orienting experiments were performed in a climate chamber under defined and controllable conditions. The obtained parameters were used as input for simulations using the ADREA-HF code using CFD for the ambient flow for verification of the model. The results were used to design large demonstrators for outdoor testing, that were built and tested in Ober Ramstadt (Germany) and Shrewsbury (UK). Both were equipped with a sensor network consisting of temperature and humidity sensors and a data processing hard- and software. Sensors integrated in a façade must be simple and robust with the aim of a long service life. Furthermore, they need to be as small as possible to be easily embedded in the ETICS, and in particular in the top coat layer, so that they remain hidden to the viewer. The algorithm of the control software was optimized during operation of the demonstrator. Thereby an intelligent ventilation system was developed, that only activates the ventilation in case it was needed. By this, the energy efficiency of the system is optimized. All results were used to design a highly integrated ventilation system that was built on a holistic façade in Ober Ramstadt.

3 EXPERIMENT/ RESEARCH

3.1 SENSOR NETWORK AND CONTROL UNIT

The temperature sensor, a Pt1000 element, is sealed with a 2-component glue, containing silver to achieve a high thermal conductivity. Being very small in dimensions, it can easily be implemented within the base coat layer of the ETICS and therefore measure the temperature very close to the surface of the wall. Thus it is completely covered by the top coat, the sensor is not visible.

FIG. 2 Left image: Temperature sensor (left) and humidity sensor (right) attached to EPS as thermal insulation material; right image: sensor pins of humidity sensor after application of the top coat

The determination of moisture content of the surface is based on a DC resistance measurement. This method measures the resistance between two pins inserted in the material. When good contact is made between the pins and the material, a path is provided for current to flow between the two pins. Characterization of current flow in wood has been the object of numerous research works (Onysko, 2008). Principally, increased moisture contents cause a decrease in electrical resistance. A similar behaviour is observed in other building materials such as concrete, gypsum or masonry and can therefore be used for plasters. Two small pins of stainless steel were fixed on a plastic holder, and electrically connected with wires (Fig. 2, left image). This sensor can be embedded in the base coat of the ETICS, so that just two small pins are visible after the façade is build (Fig. 2, right image).

These sensors (Pt1000 temperature probes and surface moisture sensors) are connected to sensor nodes. The nodes convert the analogue output signal of the sensors in digital data. Several of these sensor nodes can be interconnected and share a unique digital bus to exchange data with the Master Unit (MU) which is connected to a ventilation unit through a 0-10V signal line. When the signal is below 1.5 V the ventilation unit remains switched off. As soon as the voltage reaches a voltage of 1.5-1.6 V the ventilator switches on and air flow speed is controllable within a range of 2 V (lowest speed) to 10 V (full speed). The MU communicates to a controller, which basically consists of a computer that executes the software program implementing the data analysis and ventilation control logics. The MU is in fact a gateway that translates the commands from the controller into actions within the system. The computer could eventually be replaced with a programmable device such as a PLC, or the MU could incorporate the analysis and control functionalities. A graphical user interface allows a user to manually operate the system but also to configure how the system must behave in automatic mode, that is, operation mode which does not require human intervention.

3.2 EXPERIMENTS UNDER DEFINED CLIMATE CONDITIONS AND NUMERICAL SIMULATIONS

First experiments were performed under defined climate conditions to generate input for simulations and the validation of those. These results were then used to design large demonstrators for outdoor testing.

A unit that supplies air at regulated temperature and flow was used as prototype for these first experiments. It consists in an in-line fan and a duct air heater with built-in controls all packed in an aluminium frame structure.

Both the inline fan and the heater are commercial components from the manufacturer Vent-Axia. In order to accommodate these two components according to the requirements, a tailored mechanical structure and ductwork as well as an electrical cabinet for powering and operating safely the equipment was designed and built.

The unit (Fig. 3) can provide an air flow up to 0.23 m^3/s and air temperature rise from 8°C to 25°C above intake air temperature (depending on the air flow). Temperature rise can be increased if needed by connecting the second resistor inside the heater. There is no active regulation or control of output air humidity but a passive one instead, given that relative air humidity is naturally reduced as a result of heating. This is because active air humidity regulation can only be achieved by means of mechanical dehumidification systems that use the same basic mechanics as air conditioners, but the process is energy consuming and equipment is heavy. The whole setup was placed in a climate chamber, where the ETICS panel was placed in the center of the chamber (see Fig. 3). The climate chamber has dimensions of 2100 x 4000 x 3000 mm^3 and temperature as well as the relative humidity can be controlled. The first experiment to evaluate the drying capacity of the ventilation system was conducted without sensor measurements. The samples were wetted and the panel was weighed after different times of drying. In this way it was possible to measure the amount of water that was removed from the panel by the ventilation unit in a certain period.

FIG. 3 First prototype of the ventilation unit and test area equipped with different sensors for experiments under defined climate conditions (placed in a climate chamber)

3.3 OUTDOOR EXPERIMENTS

The testing rig of the demonstrator for outdoor tests is a wall built using commercial ETICS. The surface is exposed to the elements and divided in 4 areas from which 2 can be mechanically ventilated (test areas) and 2 remain naturally ventilated (control areas). In order to obtain results faster, one control area and one test area are deliberately treated with a solution of endemic algae specifically formulated for the experiments. Surface temperature and moisture sensors were embedded in the render and connected to the acquisition system.

FIG. 4 Construction of the demonstrator wall consisting of ETICS, sensors and ventilation unit

The demonstrator was built on a wooden plinth with the dimensions 3 x 2.5 meters. The ventilation unit (air curtain by TTL, a modified Trend 150 K-8 STE) ventilates the left half of the demonstrator, and the whole demonstrator is protected by a canopy. First, rails were installed to separate the four test areas (see Fig. 4). By that, a migration of microorganisms between the test areas is avoided. The rail in the middle of the demonstrator also has the function to block the ventilated air so that it cannot reach the right, unventilated part.

In a second step, EPS boards (Dalmatiner 032) with a thickness of 10 cm were glued on the wooden substrate and fixed with anchors (see Fig. 2). One temperature- and one humidity sensor was attached in the middle of each area. The sensors were directly glued on the EPS (see Fig. 4). After the application of the rendering including a 5 mm thick layer of base coat (Armatop 700), the mesh CT650 and 2 mm of the top coat (CT134), the pins of the humidity sensors reach through the wall by approx. 5 mm (see Fig. 2, right image).

FIG. 5 Demonstrator placed outside for outdoor testing in Ober Ramstadt (Germany)

Another demonstrator was built in Shrewsbury (UK) that was closing the gap between a technical demonstrator like in Ober Ramstadt (see Fig. 5) and a holistic house façade. Therefore a real wall was used to install the ETICS, and no separators were installed. Instead, two strips were painted in order to reduce water uptake of the ETICS top coat with the purpose of keeping a water film on the surface for a longer time, which favours algal growth. Also, the sensors in the wall were placed in the lower part of the wall instead of the centre. This location offers better conditions for biofilm growth as it is more affected by humidity retained in ground vegetation and the air from the ventilation unit is weaker. The ventilation unit is placed in the centre of the façade. 4 pairs of sensors were installed to detect the influence of the ventilated air (see Fig. 6). In addition, a weather station was installed to measure the climate conditions in front of the façade.

FIG. 6 Demonstrator on a real house façade in Shrewsbury (UK) for outdoor testing

4 RESULTS

4.1 EXPERIMENTS UNDER DEFINED CLIMATE CONDITIONS

The first trials were performed in a climate chamber at 12°C and 80% relative humidity. The results are shown in Fig. 7. The results were leveled to the same starting point. This means that the starting point of the experiments was not the same for all trials, but to evaluate the results in a more convenient way, all measurements were recalculated to a starting weight of 0 g. The blue curve shows the result without any ventilation. It can be seen, that it takes nearly 3 h to reach a stable and (visibly) dry state. The violet line shows the experiment with no heating and a low ventilation speed of approx. 3 m/s close to the exit. The experiment with medium ventilation and no heating is shown with the red line. Medium ventilation and minimum heating was used for the results shown in green colour. It can be seen, that the higher the wind speed and the higher the temperature of the air flow, the faster the panel is drying and the more water is evaporated within the given time.

The drying time can be decreased substantially. With medium ventilation the same amount of water can be removed within an hour, which would take 3 hours without ventilation. At the given conditions, the testing rig set on medium ventilation (red curve) can therefore remove approx. 30 g water of the 0,5m^2 panel within the first hour without any heating. This is a significant difference relative to the reference without ventilation, where only 15 g water where removed. However, the difference relative to the experiment with heated air (green curve) is not very high (40 instead of 30 g of water), meaning that an energy consuming heating of the air is not necessary to dry a façade.

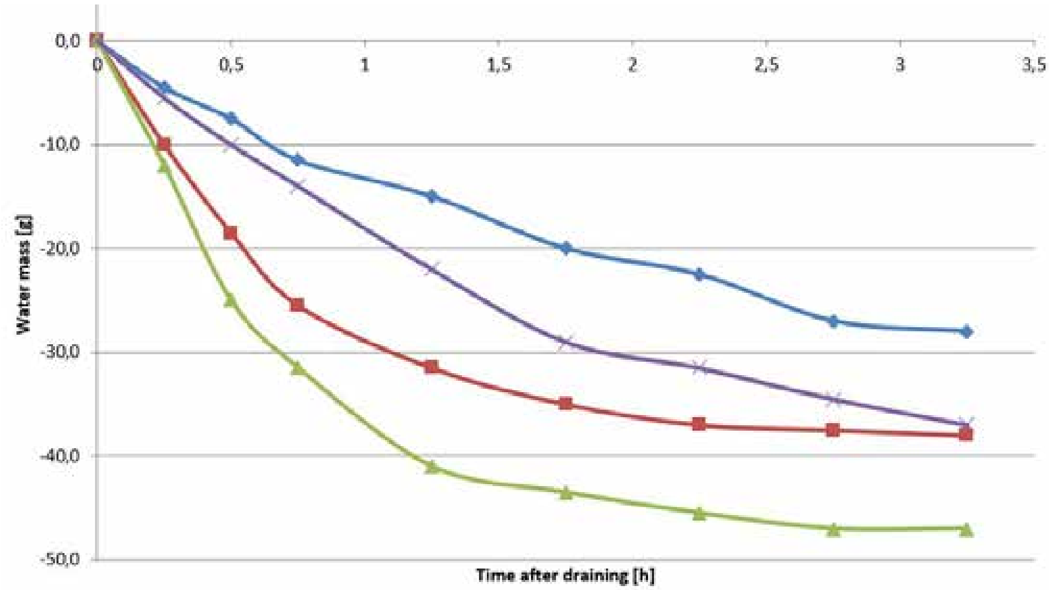

FIG. 7 Results of water mass on ETICS surface with and without ventilation. Blue diamond: reference without ventilation; violet cross: low wind velocity; red square: medium wind velocity; green triangle: medium wind velocity with heated air

4.2 SENSOR NETWORK

The combination of humidity and temperature sensor integrated close to the surface of the façade allows to determine the need for activating the ventilation unit. For the humidity sensor, two indicators are used: the value of the reading and the trend over 5 consecutive readings. If the reading value of any of the sensors is above certain threshold the wall is considered to be wet. A positive trend is interpreted as "the surface is getting wet" while a negative trend is interpreted as "the surface is drying by natural evaporation". It has been observed that during a rainfall the moisture sensor output curve remains flat at certain "saturation" value, which depends on water conductivity and plaster electrical properties. Therefore, the start of a wetting event can be recognized by the transition from a flat or negative trend to a positive trend, and vice versa, for the end of a wetting event a transition from a positive or flat trend to a negative trend (see Fig. 8).

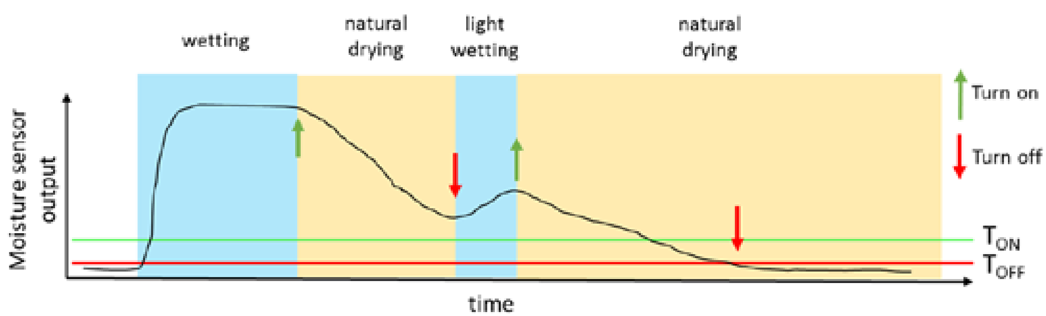

FIG. 8 Graphical representation of the behavior of the algorithm

Two thresholds (TON and TOFF) and a minimum negative trend (TRmin) are set as adjusting parameters. The reason behind the two thresholds is to introduce a hysteresis factor to avoid an erratic behaviour of the algorithm when the sensor signal shows noise or little oscillations near the thresholds.

When surface moisture starts reaching its lowest values after drying, the surface temperature is several degrees below ambient temperature caused by the evaporation energy of the water. If the ventilation stopped at this moment, in some cases, the surface temperature might be below the dew point, which would lead to condensation. In order to minimize the risk of recondensation it is necessary to restore the wall temperature at ambient temperature or at least above the dew temperature as fast as possible. This can be achieved by keeping ventilation on for an additional time (warming) that can be fixed or variable according to temperature sensor feedback.

At temperatures below 0°C, the ventilation unit does not need to be activated, since there is no growth of microorganisms at this temperature. In combination with a weather station, the ventilation is also not necessary in case it is windy.

4.3 RESULTS OF OUTDOOR DEMONSTRATORS

The ventilation unit controls the air velocity by adjusting an input signal from 0 to 10 Volts (0 being off). The air velocity was measured at different positions on each area to measure the homogeneity and the drop of air velocity over the length of the wall. For different ventilation intensities, the air flow had a velocity of 3 m/s (2V) to 12 m/s (10V) at the upper position close to the air outlet (see Tab. 1). This value dropped to approx. 50% over the length of 2 meters (lower position), so 1.5 m/s (2V) and 6 m/s (10V). There is no significant difference of the air velocity depending on the horizontal position under the ventilation unit. So the air flow covers the area in a homogeneous way.

CONTROL SIGNAL	2V	4V	6V	8V	10V
Upper position	2.0-4.0 m/s	6.0-7.0 m/s	7.5-9.0 m/s	10-11 m/s	11-13 m/s
Middle position	2.0-3.0 m/s	4.5-6.0 m/s	6.0-8.0 m/s	7.5-9.0 m/s	8.5-10 m/s
Lower position	1.5-2.5 m/s	3.0-4.5 m/s	4.0-5.5 m/s	4.5-6.5 m/s	5.0-7.0 m/s

TABLE 2 Air velocity caused by the ventilation in dependence of the control signal

To test the drying ability of the system, a first experiment was performed under defined conditions in the laboratory. The temperature was 17°C, the relative humidity of the air was 50%. There was otherwise no wind or air flow in the laboratory. The area was wetted with a defined amount of water, and after 5 minutes, the ventilation unit was activated manually. In Fig. 9, the output of the humidity sensor (above) and the temperature sensor (below) can be seen as the reaction to the wetting and the drying (time normalized to 11:55 for wetting and 12:00 for the start of the ventilation unit).

The reaction of the humidity sensor on the water can be clearly seen, followed by a first drying caused by water rinsing of the surface. After the ventilation started, the drying was accelerated depending on the ventilation intensity. For intensities of 4 to 10 Volts, the humidity sensor got back to the value that it had before wetting after approx. 8 minutes. For 2 Volts, the drying needed 15 minutes (yellow graph). For the unventilated reference (0V, red graph), the sensor got back to the originating value one hour after wetting. The drying speed is therefore at least reduced by the factor of 4 and even for very low wind speeds of 2 to 3 m/s.

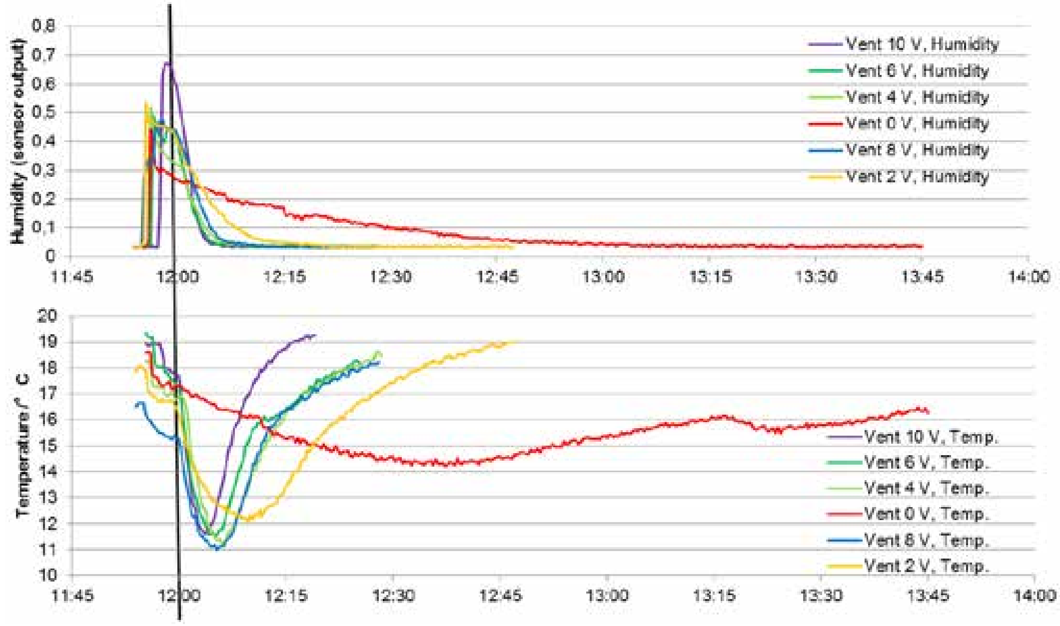

FIG. 9 Reaction of humidity sensor (above) and temperature sensor (below) on the application of water and following drying in laboratory conditions (17°C, 50% RH)

The temperature sensor (Fig. 9, below) also showed a reaction on the wetting of the wall. Since the water was cooler than the wall, the temperature dropped by 1-2 °C. When the ventilation was running, the wall cooled down to 11 °C (for the case of 4-10 V intensity) and to 12 °C (for the case of 2 V intensity). This is caused by the enthalpy of vaporization of the water. After the wall dried, the temperature was increased again to the originating value. This took 15 minutes for 10 V intensity, 30 minutes for 6-8 V intensity and 45 minutes for 2 V intensity. However for the case the ventilation is not started this process took approx. 2 hours. It is important to not stop the ventilation unit at the time the humidity sensor is back to a dry level, but also to increase the temperature by ventilating back to the ambient temperature. Otherwise, condensation of water might occur on the wall

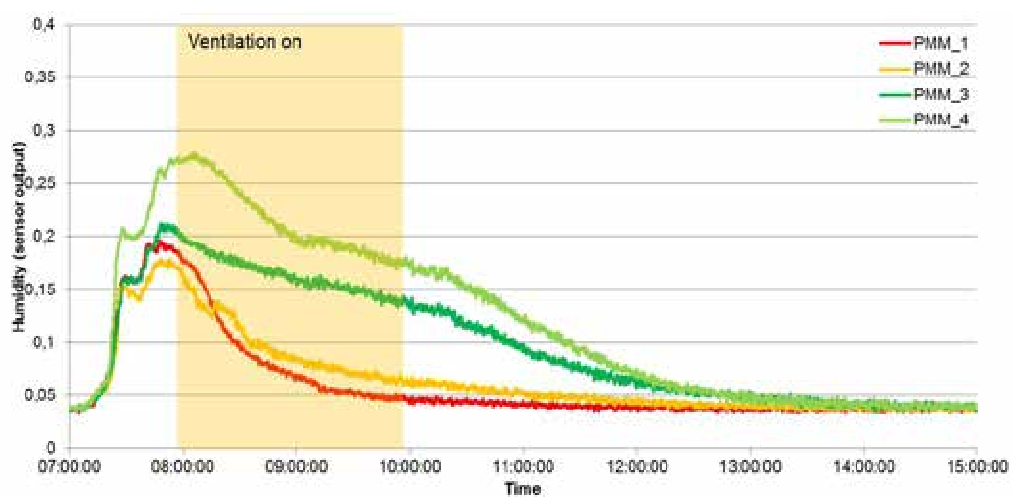

FIG. 10 Reaction of humidity sensor to a rain incident in outdoor environment

The efficiency of the drying behavior was also tested in outdoor experiments. In Fig. 10, the humidity sensor output is shown on a day with a rain incident at around 7:30 to 8 o'clock. After the rainfall stops, the ventilation unit is activated. The green curves show the results of sensors located in the unventilated area, and the red and yellow ones are on the surface, that is dried by the ventilation. The effect of forced drying by ventilation can be clearly seen. The part of the wall with ventilation is dry after 2 hours, whilst the unventilated part takes 5-6 hours to become dry.

The moisture sensors are yet not sensitive enough to reliably detect condensation on the wall surface. Therefore, as a preventive measure ventilation is scheduled every day in spring and autumn during the hours of higher condensation risk according to experience, that is, from 5:00 to 7:00 in the morning. The testing rig has allowed to observe that this is indeed an effective measure. As observed in Fig. 11 the wall surface is 1°C below surrounding air temperature which is a result of the so-called undercooling effect. This temperature difference might or might not be high enough to cause condensation, as it depends also on relative humidity and, ultimately, on whether the surface temperature decreases below the dew temperature or not. By switching on the ventilation unit the surface temperature affected by the ventilation (red and yellow line) is warmed up until reaching air temperature (black line), which will prevent condensation. On the contrary, if condensation has already settled, it will be removed. This can be seen in the humidity sensor output, where the red and yellow signals of the sensors on the ventilated area are well below the unventilated reference (green curves).

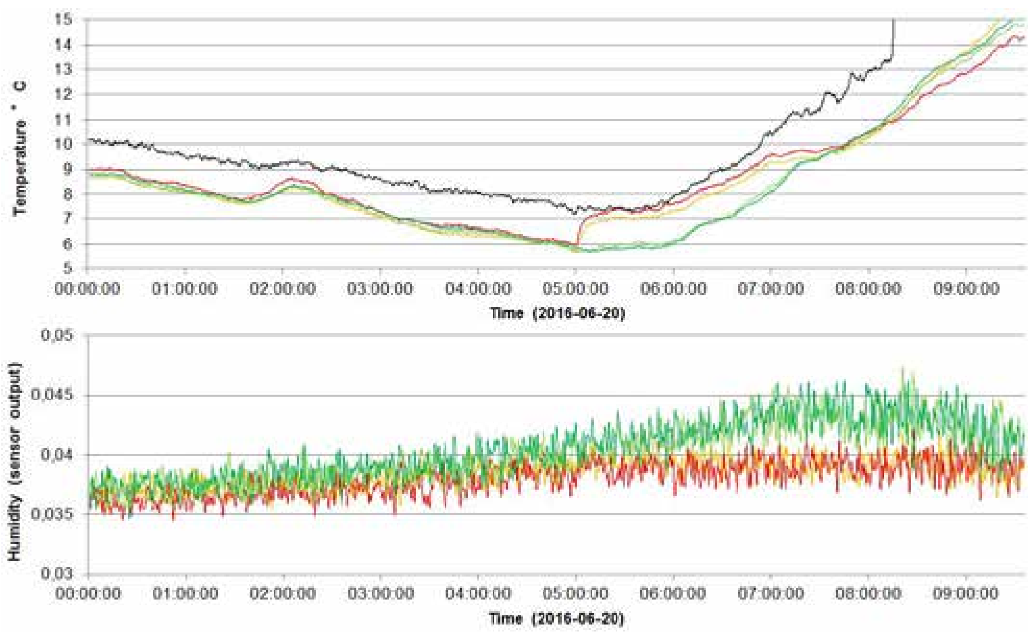

FIG. 11 Reaction of temperature sensors (above) and humidity sensors (below) on a morning with occurring condensation

4.4 DEMONSTRATOR ON A HOLISTIC FAÇADE

With the obtained parameters like air speed, moved air volume and therefore the decline of the wind speed over the length of a façade, a specially designed ventilation unit was constructed. It was also integrable in an ETICS façade to meet the need of an optically unobtrusive system. A building on the DAW facility was chosen for the installation of the ventilation system (see Fig. 12). The optical impression can still be further improved by using decorative elements that can be attached in front of the units.

FIG. 12 Images of the demonstrator of the ventilation system

After the setup of the demonstrator wall including the ventilation system, the noise level was measured in consideration of the wind velocity generated by the ventilation unit. Outside the building, in a distance of 1 m, the noise level was increased from 42 to 62 dB by the ventilation unit. Inside the building, the noise level was increased from 31 dB to 33 dB which was not noticeable. The results show that the noise level inside is acceptable. However, for the use in residential areas, a further noise insulation will be necessary to reduce the sound pressure level. By the application of decorative elements to cover the ventilation units, it should be possible to reduce the noise level to less than 50 dB which is comparable to common heat pumps.

5 CONCLUSIONS

It has been shown that façades can be dried by active ventilation of air with the aim to prevent growth of microorganisms. The ventilation system is equipped with a sensor network and is therefore controlled in an energy efficient way. The system can recognize rain incidents and their end and therefore activate the ventilation unit when it is necessary. Condensation is not yet recognized by the system, which can be solved by either combining it with a weather station or start a scheduled ventilation each morning in spring and autumn.

A prototype system was developed and integrated in a real house façade, and has been running since August 2017 without the need for maintenance.

This system is particularly useful for façades that are exposed to a high biological load, e.g. near a forest or river. It gives the house owner the opportunity to protect a particularly exposed wall of a building with a sustainable solution of algae and fungi prevention.

Acknowledgements

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Reliability and Performance Gap of Whole-Building Energy Software Tools in Modelling Double Skin Facades

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Abstract

The careful design of the façade is one of the most influential strategies to lower the energy use in a building. A double skin façade (DSF) is one type of façade that allows the interaction between the outdoor and the indoor environment to be managed in a more advanced way, by increasing the control over the energy transfer between the two environments, while providing high architectural flexibility and transparency. The design of the thermophysical performance of a DSF is a complicated process that has to take into account several aspects, such as geometric parameters, thermal properties, ventilation strategy, shading devices, and the integration between the façade and the building energy concept.

There exist different whole building energy software tools (BEST) that practitioners can use to predict the energy and indoor environmental performance of a building and to support an informed choice to select the most appropriate building components during the design phase. However, when it comes to the simulation of DSF in BEST, complexity and inaccuracies in prediction usually rise, as these envelope systems are characterised by a thermophysical behaviour that requires a more advanced modelling than the possibilities conventionally embedded in BEST.

This paper reviews the scientific literature to show evidence on how BEST are used to predict the thermophysical behaviour of DSF, together with reporting the existing modelling capabilities for some selected BEST. The purpose is to highlight the challenges associated with the modelling of DSFs and to identify the major gaps between measured performance and prediction though BEST. The findings indicate that gaps are mostly connected to the dynamic behaviour of the DSFs and in particular the airflow within the facade cavity. The challenges associated with the modelling and simulation for each software tool, and the skills necessary to recognise and implement the best-suited model among the different options available are also discussed.

Keywords

double-skin façade (DSF), whole-building energy software tools (BEST), literature review, performance gap

1 INTRODUCTION

In recent years, the need to achieve low-emission building has led to improved energy performance of building envelopes, increased building equipment efficiency (Justo Alonso, Liu, Mathisen, Ge, & Simonson, 2015), and increased harvesting of renewable energy sourced (Torcellini & Crawley, 2006). Within this context, the facade, and the building envelope in general, can play a very relevant role. Many studies have shown that the use of double skin facade (DSF) systems can lead to reduced energy use while providing high transparency, access to daylight and natural ventilation (Chan, 2011; Singh, Garg, & Jha, 2008), thus representing a possible building envelope technology that addresses all the above mentioned tasks. However, the prediction of the behaviour and design of a DSF is not a simple task. The full potential of such a technology is probably not yet reached, and the gaps between the prediction capabilities and the actual performance of these systems are important barriers that prevent their efficient implementation.

The modelling and simulation of a DSF, as more in general of an adaptive building envelope, have to accurately represent a sequence of time-varying building envelope system states (or properties), instead of a static representation of the building enclosure (Loonen, Favoino, Hensen, & Overend, 2017). During the design of a façade, practitioners and consultants can make use of several whole-building energy software tools (BEST), which allow the impact of a building envelope solution to be assessed in conjunction with all the other components of a building. The simulation of DSFs, when their impact and integration within the entire building is searched, is also carried out through BEST. However, it is questionable whether such tools can accurately describe or not the transient heat and mass transfer that occur in the complex environments of DSFs, since these tools have been developed to replicate conventional building envelope components (Loutzenhiser, Manz, Felsmann, Strachan, & Maxwell, 2007). As previously reported by Kalyanova & Heiselberg (2008), the different calculation algorithms of each tool can lead to different performance prediction and simulation errors of the DSFs. Furthermore, known phenomena occurring in DSFs are still not always replicated by BEST.

When selecting the method (and tool) for DSF modelling, attention should be primarily given to the results that are expected to be achieved. This refers to the expected level of accuracy of the results, the time required for the simulation run, and the complexity of the model and the level of knowledge of the future users.

This paper aims to provide a general overview of the use of different BES tools in replicating the DSFs behaviour. A particular focus is placed on the degree of accuracy achieved in the analysed examples, and in general of this entire category of simulation environments, and at the same time the paper also tries to identify which are the main difficulties in modelling DSFs which affect the results (both due to the user's experience lack and the tools gap).

2 METHODOLOGY

This work builds upon existing literature reviews reporting the capabilities of BEST (Clarke & Hensen, 2015), and how BEST can be used to simulate adaptive facades (Loonen et al., 2017). This paper is, therefore, a review of articles published in scientific journals showing how DSFs are modelled and simulated using BEST. Relevant publications have been searched in scientific literature databases using as keywords "double skin facade" and the name of some selected BEST (Energy Plus, Esp-r, IDA ICE, IES VE, TRNSYS.). Since the simulation of DSF with BEST is a relatively widely used research method, the search produced a significant amount of papers. This database of paper was subsequently narrowed down by applying some restrictive criteria: first of all, only recent papers published in the last decade (2008 – 2018) have been analysed. The background for this choice is the aim to analyse approaches, limitations and gaps occurring with the use of state-of-the-art BEST, while the interest on how BEST simulation capabilities has changed along the time is not the focus in this paper. However, by applying this restriction, there were no results for some of the BEST tools (ESP-r) selected. Therefore, for this case, an exception has been made, and a paper published before 2008 was included in the analysis. Secondly, to obtain information related to the reliability of the tools, only those papers presenting an experimental validation were considered.

The information gathered from these papers was then categorised according to the following criteria (see Tab. 3 and Tab. 4): BEST used, geometry (box window or multi-storey window), ventilation mechanism and path, and the type of analysis run in the paper. For each paper, the achieved accuracy in simulating the energy performance of the DSF was highlighted, in particular focusing on the prediction of the cavity temperature and airflow. Any other information that may affect the simulation results, like the number of thermal zones in which the cavity was divided, the presence or not of shading devices, etc. has also been reported in the tables, if provided in the paper.

3 CHALLENGES IN PERFORMANCE PREDICTION OF DSFS

3.1 BACKGROUND ON PHYSICS OF DSFS

Many types of DSFs have been developed over the last decades; the literature classifies DSFs according to the construction type, the geometry, the cavity ventilation and the different flow path (Barbosa & Ip, 2014; De Gracia, Castell, Navarro, Oró, & Cabeza, 2013; Haase, Marques da Silva, & Amato, 2009; Jiru & Haghighat, 2008; Oesterle, Leib, Lutz, & Heusler, 2001; Poirazis, 2004; D. Saelens, Carmeliet, & Hens, 2003). A DSF is generally composed of an outer glazed layer and an inner glazed layer, separated by an air gap that can be ventilated (either mechanically or naturally). The air gap often hosts a shading device (usually a roller shade or a venetian blind) to increase the control over direct solar gain. The external glazing and the internal glazing can be realised through multi-layered glazed units (Fig. 1). The airflow path (i.e. the origin of the airflow and the destination) can differ according to several working to fully integrated facades).

The evaluation of the thermal performances of this system is not a trivial task, and especially when the airflow is not mechanically induced. The pressure and temperature fields in the façade's cavity and surfaces are the results of many simultaneous thermal, optical, and fluid flow processes, which interact with each other and are highly dynamic. Notably, the airflow in the cavity can be highly variable when based on wind or thermal stratification, which makes the problem even more complicated. Short-wave radiative heat transfer occurs through the glazed surfaces of the façade and leads to absorption, reflection, and transmission of the solar radiation hitting the façade.

The long-wave radiative exchange occurs between the surfaces of the facades, and at the interfaces with the surrounding environments. Conduction takes place within the solid surfaces of the façade. Convective heat exchange is the crucial mechanism in the fluid-dynamics of a DSF and influences the airflow within the cavity, as well as the global heat transfer within the system.

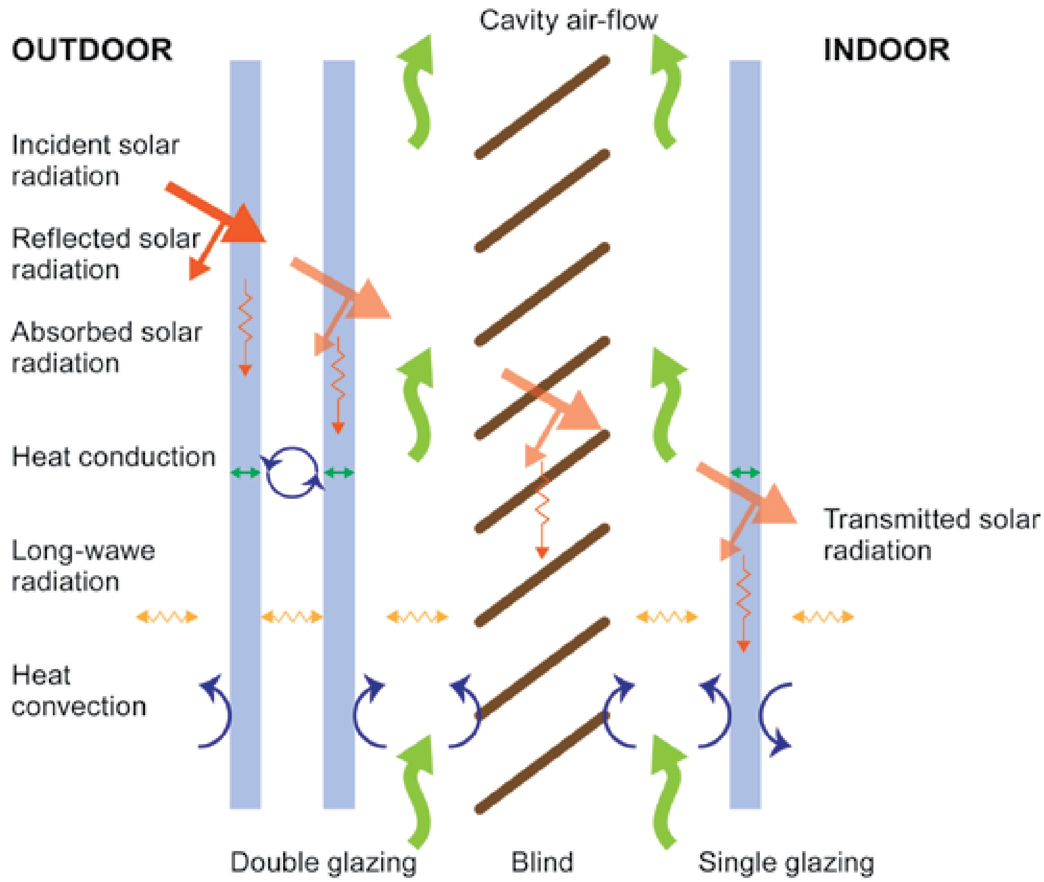

FIG. 1 Heat transfer transmission in a DSF *(Adapted from Wang, Chen, & Zhou, 2016)*

In mechanically ventilated DSF, the airflow is primarily induced by mechanical means. The fluid motion problem is, to some extent, decoupled by the thermal field within the façade construction, but it influences the thermal environment in the façade – which instead does not mainly affect the fluid motion. Conversely, in DSFs based on naturally induced ventilation, the fluid motion problem is dominated by the thermal field within the façade, which is itself affected by the airflow. This integrated thermal and fluid-dynamic problem is the primary source of complexity in modelling and simulating the heat transfer in DSFs.

3.2 DYNAMIC OPERATION STRATEGIES OF DSFS AND SYSTEM INTEGRATION

When looking at the various airflow concepts, it is important to note that all the types of DSFs (in terms of layers of glazing, shading, dimensions, etc.) can be combined with both types of ventilation (natural and mechanical) and all types of airflow concepts. This results in a great variety of DSF configurations. Fig. 2 shows the different airflow concepts that can be applied to DSFs. Moreover, DSFs act as climate responsive elements with hybrid ventilation (natural and mechanical) concepts with a possibility to change the airflow path due to different weather conditions in different seasons (Loonen et al., 2017). This requires a control system that allows changing the physical behaviour according to the outdoor climate or requirements set by a building management system. Predicting this dynamic air-flow strategy is not trivial.

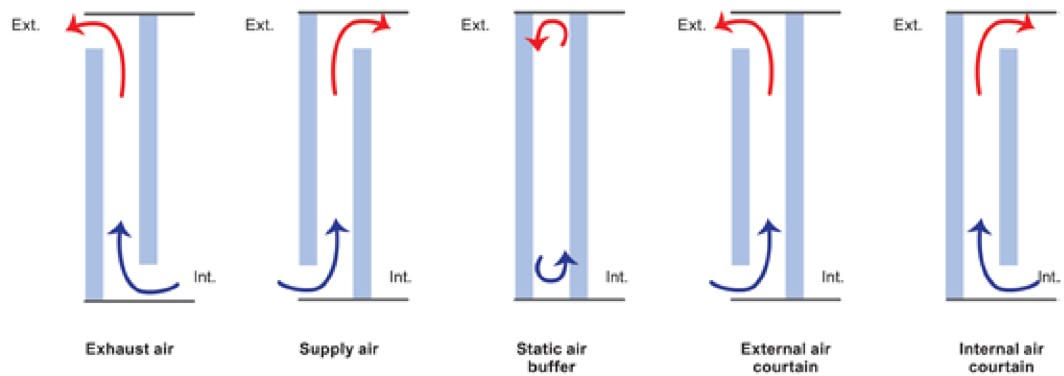

FIG. 2 Possible air-flows in double skin façades *(Haase, Marques da Silva, & Amato, 2009)*

DSF is not a traditional type of envelope that can be analysed independently from its surroundings. In particular, when it comes to mechanically ventilated façade, the coupled simulation of the building plant and this building envelope component is mandatory to obtain a correct assessment of the energy performance. This is the only way to model and assess the complex interaction between airflow in the facade and the HVAC system, and the building energy management system. Instead, when it comes to naturally ventilated facades, the boundary conditions may affect to a large extent the behaviour of the system, which in turns also affect the (indoor-side) boundary conditions. These are the reason why, regardless of the ventilation mechanics, all the different systems (façade, room, plant) need to be simultaneously simulated in order to optimise/verify the individual and overall performance, and in such a context whole-building energy simulation is an essential tool (Dirk Saelens, Roels, & Hens, 2008).

4 SIMULATION TOOL OVERVIEW - MODELLING POSSIBILITIES AND LIMITATIONS

A large number of software tools are available for predicting the energy and comfort performance of buildings (Crawley, Hand, Kurnmert, & Griffith, 2008; Crawley, Lawrie, Pedersen, & Winkelmann, 2000; Hand, 2011; S.A. Klein & et al, 2010; Sanford A Klein, 1976). Because these software tools are usually employed to determine the energy use of the whole building, the implementation and adaptability of advanced building components are not the primary consideration in conventional BEST (Oh & Haberl, 2016). Some extensive literary reviews of BEST can be found (Attia, Hensen, Beltrán, & De Herde, 2012); among them, the recent work of Loonen et al. (Loonen et al., 2017) focuses on the review of the opportunities for modelling adaptive building envelope systems (a broader category than DSF) in state-of-the-art BEST. In this work, the focus is placed on five simulation tools EnergyPlus, ESP-r, IDA ICE, IES VE, and TRNSYS) and their challenges in replicating the physical behaviour of adaptive facades. The background for the selection of these five BES tools lies in their popularity and complexity, and it is possible to state that they represent today the state-of-the-art tools for whole-building energy simulation. The selection of these software tools was based on the following criteria:

- Extensive building envelope modelling capabilities, as identified by Crawley and co-authors (Crawley et al., 2008)
- Subject to active development by their development team or user community;
- Thorough validation through compliance with ANSI/ASHRAE Standard 140 (BESTEST) and other quality assurance procedures;
- Use in both research and consulting engineering practice;
- International users;

- Based on the work of (Loonen et al., 2017), this paper also limits the analysis of the simulation possibilities and challenges in the simulation of DSF through BEST to the five software mentioned above.

4.1 HEAT TRANSFER PHENOMENA

The operational mode of the DSF can vary according to its function in one building or another, but the design of the DSF cavity is more or less the same: two layers of fenestration, separated with the air gap, which, in most of the cases, include a shading device. No matter what is the operational strategy of the DSF, the air temperature in the gap is the result of the solar radiation absorbed by glazing and/or shading device, the heat losses/gain from/to the cavity and from/to the ventilation airflow. As a result, the air temperature in the DSF cavity is mainly the result of the convective and radiative heat transfer between the heated surfaces of glass/shading and air (convective) and among all the different surfaces (radiative). Conductive heat exchange plays a significant role if one of the two transparent layers is a single glass pane, while if insulated units are adopted the weight of this mechanism on the overall behaviour of the system is limited. The floor or ceiling and side walls of the DSF rarely have significant importance, as in real life, the weight of their areas is minimal compared to the area of fenestration and shading (except DSF with very wide cavity, or DSF in façade module with reduced length). The estimation of the convective heat transfer is relatively more straightforward for the mechanically induced flow motion compared to the naturally driven flow, where the convection heat transfer depends on size, shape, orientation, flow regime, temperature etc. Different BES tools integrate different approaches for the estimation of the conduction, convection and radiation heat exchange coefficients. Concerning the selected 5 BES tools, the different approaches are illustrated in Tab. 1.

In the past years, to solve the heat transfer conduction problem, the most commonly adopted methods by BEST have been response factor techniques(Thermal response Factors (TRF) or Conduction Transfer Function (CTF)). This solution is considered computational efficient but with some limitations (it can only be applied if the thermophysical properties of the assembly are constant along the time). Numerical models based on Finite Difference (FD), Finite Volume (FV) and Finite Elements (FE) methods are used to modelling temperature evolution in systems with time-dependent material properties. These numerical methods, adopting an iterative procedure, treat the building envelope surface as made of discrete capacitances and resistances. For building walls modelled in one-dimension, a reasonable computational speed for annual energy analysis can be achieved with conventional simulation tools (Spitler, 2011). Model calculations to estimate the heat transfer of DSFs thought BEST do not usually include thermal storage effects because these used to be not so relevant when it comes to modelling transparent materials. However, this approach is not entirely correct when it comes to analysing a DSF. (Freire, Mazuroski, Abadie, & Mendes, 2011).

Considering that BEST cannot implement detailed numerical analysis (CFD) to solve convective heat transfer under transient conditions because of the resource-intensity of such methods, the convective heat transfer is usually assessed through convective heat transfer coefficients (hc) calculated using empirical correlations. For external building surfaces, these coefficients (hc, ext) are essential to calculate convective heat gains and losses from building facades and roofs to the environment. They are complex functions of, among other factors, building geometry, building surroundings, building facade roughness, local airflow patterns and temperature differences. The work of (Mirsadeghi, Cóstola, Blocken, & Hensen, 2013) provides an extensive overview of such models for HC, ext calculation and their implementation in BES tools. The considerable uncertainty in predicting these coefficients is translated into a different approach used by every software. Some of them, like Energy Plus or ESP-r, have several models implemented, providing the user with a broad range of options, giving the possibility to choose the most appropriate model for the specific problem.

Other programs rely only on one model while others simplify the issue without implementing any empirical model and by using a fixed value for hc, ext.

The calculation of the internal convective heat transfer coefficient is not much easier than the external one. It has to consider the effect of flow driving forces from mechanical and buoyancy forces. Several models are available (Peeters, Beausoleil-Morrison, & Novoselac, 2011) and not every BES tools adopt the same (Beausoleil-Morrison, 2002).

Usually, the coefficient is fixed as a constant value or, at most, the programs make the coefficients depend on the velocity and temperature difference between the surfaces. The most adopted model to estimate developed by (Alamdari & Hammond, 1983) and (Beausoleil-Morrison, 2000).

For the calculation of the radiative heat exchange, different methods are applied in BEST. The main difficulty in calculating radiation in an enclosure composed of diffuse grey surfaces arises from the treatment of the multiple reflections. (Le Dréau, Heiselberg, & Jensen, 2013) Some of these techniques are based on the calculation of view factors Fi–j between the different sections. Radiance methods can be applied to calculate with a higher precision radiative heat exchange in the short-wave region. However, because of the computational resources necessary to carry out these calculations, such an approach is often not used in BEST when it comes to DSFs.

		ENERGY PLUS	ESP-R	IDA ICE	IES –VE	TRNSYS
CONDUCTION SOLUTION METHOD		CTF, Finite difference[1]	Finite volume	Finite Difference	Finite difference	CTF[2]
Convection	**External**	6 empirical models[3]	12 empirical models[3]	Single empirical model (McAdams, 1954)	Single empirical model (McAdams, 1954)	Fixed value
	Internal	Several models[4]	Buoyancy correlations of (Beausoleil-Morrison, 2000)	DNCA (Brown & Isfält, 1974)	Buoyancy correlations: (CIBSE, 1986) or (Alamdari & Hammond, 1983)	(Beausoleil-Morrison, 2000)
Radiation		n-surfaces interaction, infinite reflections (exact solution)	2- and 3-surfaces interaction, infinite reflections	n-surfaces interaction, infinite reflections (exact solution)	Fresnel Equations applied to 2 surfaces interaction, 10 angles of incidence, infinite reflections	n-surfaces interaction by using (Gebhart, 1961) factors

1 By default, EnergyPlus uses the CTF method, but it was recently extended with a new finite difference scheme for conduction, to allow for modelling temperature- or time-dependent material properties (Pedersen 2007; Tabares-Velasco and Griffith 2012). The usage of this new approach has been largely unexplored in the literature.

2 Simulation users can also choose to bypass the CTF approach by coupling TRNSYS Type 56 with finite element or finite difference schemes such as Type 260 or Type 399 (Kosny 2015)

3 The work of (Mirsadeghi et al., 2013) identify 17 different models used in BPS tools

4 There are four different settings to direct how EnergyPlus managers select hc models during a simulation. There are numerous individual model equations for hc in EnergyPlus to cover different situations that arise from surface orientations, room airflow conditions, and heat flow direction (Energy Plus, 2010)

TABLE 1 Characteristics of whole BPS tools with respect to conduction, convection and radiation heat exchange

4.2 AIRFLOW MODELLING

Several numerical modelling approaches have been applied when it comes to studying DSFs (De Gracia et al., 2013). Among these, the airflow network model can provide fast, useful information about bulk flows without consuming high computational resources, and is usually integrated with a thermal network, and a building energy model, by solving the heat balance and the pressure balance in each node (Zhou & Chen, 2010). A "node" is used to describe each zone connected by one or more airflow paths, and external nodes characterise the external conditions. This ap-proach is the one used by the majority of building performance simulation tools, and it can be applied either if the DFS is mechanically or naturally ventilated.

The airflow path calculations are based on the Bernoulli's principle. Some properties, like wind and temperature outside the building, are described in the external nodes, while the indoor air properties are described in the internal nodes. Those nodes are then interconnected through flow paths, such as crack, openings, or windows. The conservation of mass equation is applied to each of the system's nodes; an airflow is attributed to the pressure differences between the nodes, taking into account the air motion due to the wind and the temperature difference across the opening resulting to buoyancy-driven flow (Zhai, El Mankibi, & Zoubir, 2015). This method applies either the orifice law or the power-law relationships for determination of the airflow rate by mean of the pressure difference (Awbi, 2002). The application of one or another relationship is a sensitive matter, as the classic orifice equation is more suitable for the large openings and fully developed turbulent flow, while the power-law equation is more flexible and can be adjusted to different conditions and opening sizes via the exponent n and coefficient C (Kalyanova, 2008).

When calculating the airflow in naturally ventilated facades, the approach used to determine the infiltration rate in building simulation is usually adopted. The most used methods are (1) the crack method (Bring, Sahlin, & Vuolle, 1999) and (2) the Effective Leakage Area (ELA) method (ASHRAE 62.2, 2016). The crack method requires the use of input data that can be hardly found in the literature. For this reason, the ELA method is more often adopted, even if is a more simplified approach. ELA can in fact make use of the results of the blower door test or tabulated values.

		ENERGY PLUS	ESP-R	IDA ICE	IES –VE	TRNSYS
Influencing parameters in the flow model	Wind force	X	X	X	X	X
	Wind fluctuations	-	X	-	-	-
	Buoyancy	X	X	X	X	X
Leakage area		Crack method or Effective Leakage Area (ELA) method	Crack method	Crack method or Effective Leakage Area (ELA) method	Crack Flow Coefficient (AIVC, 1994) [1]	Crack method
Airflow - Thermal network coupling		DSF component (Airflow Windows) Or Airflow network model (AIRNET)	Airflow network model	DSF component Or Airflow network model	Airflow network model (MACROFLO)	Airflow network model (CONTAM Or COMIS -TRNFLOW)

1 The equation used represents the best fit to a large range of experimental data analysed by the Air Infiltration and Ventilation Centre

TABLE 2 Air-flow models used in the BES tools

The calculations of the airflow in a naturally ventilated (multizone) building, however, is the one that makes the users face more difficult issues (Kalyanova & Heiselberg, 2008), as a series of challenges is seen, due to:

- the wind speed reduction from the meteorological data to the local microclimate near the building
- the determination of the wind pressure coefficients

— how to decide on appropriate discharge coefficients and pressure loss coefficients in general
— how to agree on an appropriate relation between pressure loss and air flow rate through the opening (determination of coefficients in the relationships).

5 ANALYSIS OF CASE-STUDIES IN LITERATURE

Some of the recent studies (2008 – 2018) on DSFs have been analysed in this paper to underline better the capabilities and limitation of the various software (Table 3). For each software, among the numerous papers available, the analysis focuses only on those studies that have validated results with experimental data. Except one software tools (IES-VE), it was possible to find papers where numerical simulations were compared to experimental data. The software tool that does not present empirical validation is however compared to additional simulations (CFD). Many of the analysed papers deal with naturally ventilated facades, and this is because most of the difficulties encountered are related to the estimation of the air flow inside the cavity. In a mechanical ventilated façade, this parameter is given as input of the HVAC system and therefore leads (in general) to lower model complexity and associated uncertainty.

Software	Reference	Type of Double Skin Façade technology	Type of analysis (Thermal/ Visual/ Airflow)	Validation of Results	Cavity Ventilation	Airflow path	Shading devices in the cavity	Type of shading device
EnergyPlus	(D. W. Kim & Park, 2011)	Box Window	T, A	Yes	Natural	Varying[1]	Yes	Venetian blind
EnergyPlus	(Anđelković et al., 2016)	Multi-storey	T, A	Yes	Natural	External air curtain	No	-
ESP-r	(Leal et al., 2004)	Box Type	T, A	Yes	Natural	External/ Internal air curtain[2]	No	-
IDA ICE	(Eskinja et al., 2018)	Box Type	T, A	Yes[3]	Mechanical	NA	No	-
IES VE	(Pomponi et al., 2017)	Multi-Storey	T, A	No[4]	Natural	External air curtain	Yes	Venetian blinds
Trnsys	(Y. M. Kim, Kim, Shin, & Sohn, 2009)	Multi-Storey	T, A	Yes	Natural	Buffer mode	Yes	Venetian blinds
Trnsys	(Khalifa et al., 2015)	Box Window	T, V, A	Yes	Natural	Supply air	Yes	Roller blind

1 The DSF was operated in four different ventilation modes (supply air, exhaust air, internal air curtain and external air curtain) by controlling the four ventilation dampers located at the top and bottom of exterior and interior glazing. During the experimental period, the ventilation modes were changed arbitrarily at 2-h intervals.
2 The absorptive glazing is placed externally during the summer analysis and internally during winter.
3 The results were also compared with the MATLAB-based model HAMBASE
4 IES VE results are compared against those obtained from a FLOVENT model, a computational fluid dynamics (CFD) software package.

TABLE 3 List of recent papers analysing the energy performances of double skin facades

Software	Reference	Number of thermal zones	Cavity width	Cavity height	Convective heat transfer method		Temperature comparison	Airflow comparison	Average error		R^2	
					Exterior	Interior			°C	m/s	T	V
Energy-Plus	(D. W. Kim & Park, 2011)	3	50 cm	2.16 m	MoWITT	ASHRAE Vertical Wall algorithm	Over-estimation	Over-estimation	3.89	0.99	-	-
Energy-Plus	(Anđelković et al., 2016)	-	NA	NA	MoWITT	Adaptive Convection Algorithm	Underestimation	Over-estimation	-	-	0.93 – 0.96	0.86
ESP-r	(Leal et al., 2004)	up to 16[1]	NA	NA	Different settings[2]	Different settings[3]	Overestimation	Under-estimation	2.3	0.11	-	-
IDA ICE	(Eskinja et al., 2018)	NA	NA	3.6 m	-	-	Overestimation	-	-	-	-	-
IES VE	(Pomponi et al., 2017)	8[4]	100 cm	3.5 m[2]	-	-	-	Under-estimation	-	-	-	-
Trnsys	(Y. M. Kim et al., 2009)	5	50 cm	3.6 m	-	-	-	-	1.87	-	0.96 - 0.98	-
Trnsys	(Khalifa et al., 2015)	6	30 cm	2.7 m	-	-	Under-estimation	Over-estimation[5]	0.5	-	0.98	-

1The paper presents a parametric study of the number of zones into which the window air channel should be divided and the comparison of results with measurements in the test cell. The average errors are related to the case of 4 thermal zones were

2 The default setting (McAdams method) and a fixed value of $h= 17.5 W/m^2$

3 The default correlations (Alamdari-Hammond), fixed values $h= 3 W/m^2$ and $h= 8 W/m^2$, Bar-Cohen and Rosenhow correlation and the SOLVENTcorrelation developed by Molina and Maestre. The average errors listed in this table are related to the default correlations, which give the same results of the fixed values.

4 One per each floor

5 Since no measurements of airflow rates were available from the experiment, the data have been compared with the quantities during winter and summer measurements presented in Saelens (2000). The average simulation resulting airflow rates are in a good agreement with measurements.

TABLE 4 Comparison of the estimated results and the experimental data

The results of the different models analysed are gathered in Table 4. It is possible to notice that there is not a common trend among the different tools in overestimating or underestimating the experimental results. It is also essential to point out that most of the studies do not report the validation of the mass flow rate, but the quantity used as performance parameter in the validation process is a temperature (either a surface temperature of the different glass layers or the temperature of the air in the cavity).

In their analysis, Kim and Park (2011) simulate different flow paths in a naturally ventilated box window DSF by using Energy Plus; they identify in the airflow calculation algorithm as the first responsible of the difference between simulations and measured data. At the same time, the significant differences in estimating the surface temperatures, according to the authors, is understood to be caused by the applied convective heat transfer coefficient correlation. In a similar study, where a multi-storey DSF of an office building is modelled using EnergyPlus, Anđelković, Mujan and Dakić (2016) identify the main obstacle to be the time step-resolution of the software, which is not low enough to predict the airflow correctly in the cavity. The authors adopt the statistical indicators provided by the Guideline 14 (ASHRAE, 2002; DOE, 2008; EVO, 2012) to assess the level of simulation model accuracy. Leal, Erell, Maldonado and Etzion (2004) use ESP-r to simulate a box window in which an absorptive glazing with a low shading coefficient is adopted as a shading device. The authors try to establish a correlation between different parameters and the accuracy of the results. It is found that the most critical parameter is the number of zones into which the window is divided; the number of vertical divisions is especially critical, but dividing into more than four zones brought only marginal improvements. The second parameter in order of importance is the heat transfer coefficient. The least essential parameter is the local pressure loss coefficient.

By means of the software IDA ICE, Eskinja, Miljanic and Kuljaca (2018) investigate the air temperature in the cavity of a box window using the airflow network approach. In their analysis, the authors compared the results with the experimental results of a scaled system, showing some disagreement with the results, but the background for this behaviour is not of easy interpretation.

The model applied by the software to calculate the convective heat transfer is identified, in another study (Pomponi, Barbosa, & Piroozfar, 2017), as the reason of the inaccuracy of the simulation results. The paper analyses a multi-storey building with a naturally ventilated DSF. In the authors' view, IES-VE applies a method which is the most indicated for DSF buildings, but yet not entirely suitable to narrow cavities. Such an approach underestimates the heat transfer to the air, subsequently causing a weaker buoyant force to drive air through the channel.

Kim et. al (2009) use TRNSYS to investigate only the winter thermal performance of a multi-storey façade. The validation of the simulation has been done through experimental data collected from a three-story building with double skins on its eastern and western façade located in South Korea. The analysis, conducted only in the buffer mode, shows a good agreement of predicted temperature inside the cavity and the experimental data, also taking into account the effects of the natural ventilation on it.

Khalifa and co-authors (Khalifa, Ernez, Znouda, & Bouden, 2015), by mean of the same tool, evaluate the thermal performance of a single-storey naturally ventilated DSF, and a good agreement with experimental results is found in the evaluation of the surface temperatures, (the absolute value average error does not exceed 0.5°C). The differences occurring are due to, in the authors' opinion, the combined effects of error propagation introduced by the simplification in the geometry (a single-channel cavity) and the lack of accuracy in some boundary conditions (no accurate or unknown data on relative humidity and wind speed and direction).

6 DISCUSSION AND CONCLUSIONS

In both research and engineering practice, it is increasingly common to adopt building energy software tools to study the energy performance of a double skin facade. Even though several studies on this topic have been carried out in the last years, different challenges usually arise when it comes to the estimation of the thermal behaviour of this complex type of envelope through models implemented in and modelling techniques adopted by conventional building energy software tools. In particular, the most relevant challenge is related to the modelling and simulation of the airflow inside the cavity, and how this is reflected in the heat transfer phenomena within the cavity. This difficulty affects, especially in naturally ventilated facades, not only the prediction of the airflow rate, but also the values of the temperatures of the various surfaces and the cavity air temperature, and in turn the entire energy flown through the facade.

There are substantial evidences in the literature which demonstrate the importance of modelling accurately the internal surface convective heat exchange within building simulation programs. Despite this, most programs still employ simplified approaches because of the computational efficiency of these methods when compared to more refined modelling approaches. In the studies available in the literature where the cavity air velocity is analysed, a high level of disagreement between measurement and simulation is reported. The uncertainty in the prediction of the airflow rate is the primary outcome of this analysis, and as previously mentioned, the airflow rate, the flow regime, the convective and the radiative heat transfer have all together an impact on the resulting air temperature in the cavity. Among the parameters that play a role in determining the accuracy of the results, the number of thermal zones into which divide the cavity and the correlations adopted to determine the convective heat exchange coefficient seem to have the higher impact.

The analysis has shown that there is not a particular trend in terms of overestimation or underestimation of the physical quantities based on the selected BES tool, or on the type of facade constructions. On the contrary, discrepancies seem therefore more linked to the intrinsic limitation of the entire class of BES tools rather than to some specific conditions. Such result is, unfortunately, of little use for the professional community, whose task is to select the most suitable BEST in the design phase, and for the research community, whose goal is instead to develop further the capabilities of BES tools to simulate more advanced building envelope systems. These results, in fact, does not show that one tool is superior to another, nor point towards some clear directions to be followed in order to improve these tools. Nonetheless, the authors' interpretations of the discrepancy between simulations and experiments can be useful information to identify areas of possible developments of BES tools.

In order to be considered successfully validated, a model has to demonstrate the consistency of its predictions for all parameters, and have a certain agreement with the experimental data. For the time being, it is questionable whether or not the models are consistent enough when comparing the results of simulations with the experimental data. Furthermore, the analysis has also shown that only a few authors present their results referring to standardise statistic indicators (the only one adopted in the surveyed papers is R2). Moreover, the validation is often limited to few physical quantities, while different aspects than temperature values (and, very seldom, airflow rate) are usually not considered (such as, for example, transmitted solar irradiance, convective and radiative, in the long IR region, heat fluxes). This is mainly due to the fact that, in the case of double skin facades (and building components in general), guidelines on validations of simulation tools are not available, and there is no standard that can provide a procedure, nor statistical accuracy level indicators (MBE, RMSE, R2, CVRMSE, etc.) to be adopted. Currently, there exist some standards, such as the ASHRAE Guideline 14 (ASHRAE, 2002), which provide a minimum acceptable level of performance, identified through statistical metrics, for models of entire buildings through BES tools. However, a similar standard dedicated to the validations of models of building components does not exist. Hence, the evaluation of the performance of different BES tools in simulating the behaviour of DSFs is not a standardised procedure, and it results in a lack of common methodologies. The development of more robust modelling approaches and strategies for the simulation of complex building envelope systems calls therefore not only for more detailed and accurate physical-mathematical modelling and efficient algorithms but also for shared procedures to evaluate and benchmark the newly proposed models or simulation approaches, which can make the validation process more reliable.

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A Simulation-Based Framework Exploring the Controls for a Dynamic Facade with Electrochromic Glazing

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Abstract
An automatically-operated dynamic facade can play an important role in reducing building energy consumption while providing a comfortable indoor space. However, due to the complexity of the facade components integrated with lighting and HVAC systems, a further investigation on a multi-objective control strategy is required. An electrochromic window (EC) is adjustable for the amount of solar radiation transmitted into the room.
This paper proposes a simulation-based framework to explore different possible states of a south oriented window with EC, in order to find the most appropriate state at every timestep through a ranking algorithm. Based on the annual simulated results of all the possible combinations (64 cases in this study) using Radiance and TRNSYS a ranking algorithm compares the performance for visual comfort, thermal comfort, and energy demand. The outcome is a set of window states with the best performance at every timestep; and can be used to control a window. After re-ranking and considering the impact of selected window states and thermal inertia, the final output will be achieved as an annual profile which can be used to control the dynamic facade effectively.
Finally, the influence of the proposed control was investigated by comparing the final annual results with the results of some conventional control strategies such as radiation-dependent shading and direct sun glare control.

Keywords
building simulation, dynamic facade, simulation-based control strategy, electrochromic glazing (EC), radiance, TRNSYS

1 INTRODUCTION

Dynamic facades with adjustable optical and/or thermal properties are the result of being able to interact dynamically with environmental conditions to improve building performance (Loonen 2010). Automatically-operated dynamic facades can play an important role in reducing building energy demand while maintaining high levels of indoor environmental quality (Bakker et al. 2014). However, the complexity of the relationship between the state of the facade and energy requirements for cooling, heating, and electric lighting (Lee, E. et al. 2015) shows that only a multi-objective (considering all aspects of visual and thermal comfort and energy saving) control strategy can be effective.

Traditional solutions for controlling radiation, such as shades or blinds, usually block the view to the outside. For high-rise buildings in locations with high speed winds electrochromic windows (EC) are a fitting solution that can adjust the amount of radiation transmitted into the room by a small change in DC-voltage while preserving the preferable view to the outside. EC provides effective sun protection specially for reducing the annual cooling and lighting electric energy, especially in cooling dominated climate (Sullivan, R. 1996), while it preserves unobstructed view to the outside. However, it comes with some potential problems as well:

- Changing from one transmittance state of EC to the other state (dark or clear) takes several minutes (5 min to 15 min), which should be considered especially for controlling the system under rapid changes of sky conditions for a partially cloudy sky.
- Even in the fully tinted state, EC is not completely able to control glare and direct sunlight (Clear, R. et al. 2006).
- An EC window is not able to block the transmitted radiation only for a specific direction. It reduces the transmissivity uniformly on the glass pane by coloration. But venetian blinds are able to tilt and block direct sun rays and keep rest of the window area clear and unobstructed.
- A color shifting effect due to the window combinations of tinted states, which makes the transmitted light bluish. With visible transmittance (T_V) lower than 11% the Color Rendering Index (CRI) falls below 80, which is the minimum acceptable value for office spaces (Piccolo, A., & Simone, F. 2015).

Despite evidence that EC windows can improve building performance, there is still no best effective trade-off control strategy that considers both energy and comfort aspects while being easy to implement. Recent studies have suggested that rule-based controllers (e.g. heuristic) for smart windows could provide better performance compared to the optimal controllers based on genetic algorithms and model predictive control (Dussault, et al. 2016 & 2017).

The main objective of this study is to define a simulation-based framework that explores the possible states of the window, evaluates the corresponding performance at every timestep and uses this data to control EC windows.

2 METHODOLOGY

A simulation-based framework is described in this paper in order to explore different scenarios for a south oriented window with an electrochromic glazing system. It is possible to find the most appropriate window state at every time step by exploring pre-calculated hourly results for all possible window combinations. Using the top ranked selected states can reduce energy demand and provide desired indoor thermal and visual comfort.

First, all possible window combinations (64 cases) were applied in the building model for TRNSYS and Radiance to perform parametric simulations. After running all the simulations, the performance for visual comfort (glare, useful daylight), thermal comfort (local PMV), and energy demand (Q sensible) can be compared at every time step (1 hour in this study). For every parameter certain criteria were checked by using weighted penalty functions; selecting the most appropriate states is then possible by searching for the cases with minimum total penalty. The outcome is a set of scenarios which contain the top ranked window states with the best performance at every timestep (referred to as "top-ranked scenarios" in this study).

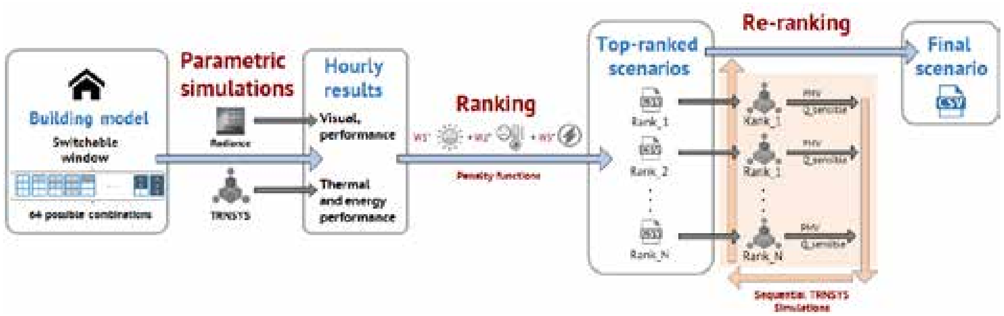

FIG. 1 The exploration procedure in the proposed framework

Because of the impact of window state selection on thermal behaviour of the building, the selected top ranked scenarios should be re-ranked through sequential TRNSYS simulation runs that take the window states impact on thermal inertia into consideration. After running parallel simulations for a year, the final output (final scenario) will be generated as an annual profile of the most appropriate window states which have the best-simulated performance. This profile can be used later to control the dynamic facade effectively. The exploration procedure in the proposed framework can be divided into three main steps (Fig. 1):

2 Parametric simulations (Radiance and TRNSYS) for all possible combinations (64 cases) to generate all the necessary hourly results to evaluate the performance.
3 Ranking procedure based on the penalty function to search and select the top-ranked scenarios.
4 Re-ranking procedure to check the thermal inertia impact (by running sequential TRNSYS simulations) and search for the final scenario with the best performance among the top-ranked scenarios.

Finally, this paper investigates the influence of the proposed simulation based control by comparing the annual results with the results of some conventional control strategies such as radiation-dependent shading and direct sun glare control.

2.1 MODEL DESCRIPTION

The model represents an office room with a south oriented fully glazed window (window area of 14 m^2, 90% Window to the Wall Ratio) divided into three different zones (top, middle, bottom). The room has the following dimensions: 6 m length, 5 m width, and 3.3 m height (30 m^2 floor area). The layout of workplaces is defined for four seated occupants executing common office tasks (Fig. 2). The same geometry is used for lighting and thermal simulation (with some simplifications and adjustments).

The weather data (EPW file) for Mannheim (49.4875° N, 8.4660° E) was used for both thermal simulation as well as for lighting simulation (for generating sky). Because of the weather files' limitation and in order to reduce the amount of simulation runs, a simulation timestep of one hour was used. However, this method can be used for smaller time steps if weather data is available. Since a one-hour timestep is greater than the time required to switch EC from one state to the other (about 5 to 10 min), it was assumed that EC properties are constant over a timestep. It was also assumed that environmental conditions stay constant over an hour.

Verified simulation tools such as Radiance (Ward, G., Shakespeare R. 2004; Ward, G. et al. 2011; McNeil, A. et al 2013) and TRNSYS enhanced with the BSDFs (Bidirectional Scattering Distribution Functions) were used in this study. Modeling switchable window systems such as EC was handled by using the TRNSYS CFS feature and variable option for shading configuration input (Hiller, M., Schöttl, P. 2014; McDowell et al. 2017). Radiance has also been used via Ladybug tools (Roudsari M. 2018) to parametrize the window properties (including different BSDFs) for annual simulation with a 3-phase method and window groups option. Therefore, at every simulation timestep the detailed optical and thermal properties of a window can be dynamically adjusted. The available daylight at workplaces (simulated in Radiance) was input into TRNSYS to calculate the electricity for the artificial lighting and internal gain so that the integration of energy and daylight simulations is achievable. This improves the reliability of simulation results and the exploration procedure.

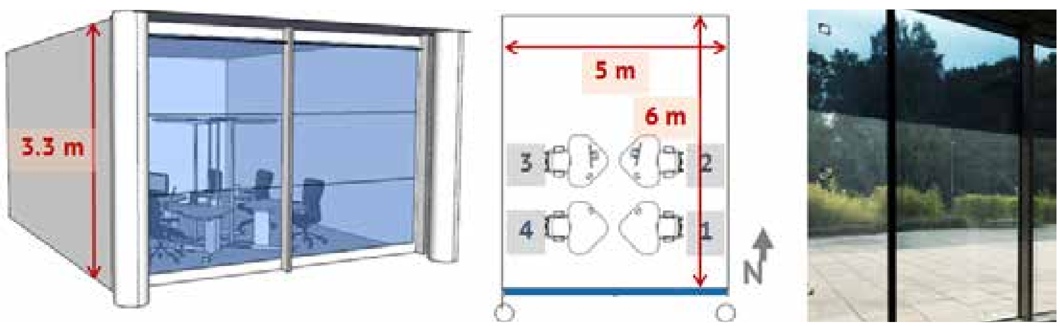

FIG. 2 left: The model with 3 different zones for electrochromic glazing (top, middle, down), middle: the plan layout, right: window view from inside with different tinted states

2.2 MODELING THE WINDOW SYSTEM

In order to model electrochromic glazing in Radiance and TRNSYS the glazing system configuration was defined in LBNL Window software under CEN environmental conditions. Detailed angle-dependent properties are available in the IGDB (International Glazing Database available online) and can be used in the software. Fig. 3 shows that the window is made of two different layers. A laminated layer includes an electrochromic film (7 mm, layer 1, SageGlass_7_SR2_60cl), a 15.5mm gap filled with air (10%) and argon (90%), and a coated layer (12.9mm, layer 2, 6_6_LowE180) with a U-value of 1.214 $[W/m^2K]$. The optical and thermal properties of the EC window model (for different states) can be exported as "Energy Plus BSDF IDF File report" xml files which contain the BSDF data (full Klems BSDF matrix with 145 patches) for daylight and thermal simulation. Tab. 1 shows the center of glazing Solar Heat Gain Coefficient (SHGC), and four possible visible transmittance (Tvis) and solar transmittance (Tsol) states at normal incidence. This yields the total number of 64 possible window combinations (4^3, for four different EC states and three different window zones: top, middle, and bottom) which need to be run at the parametric simulations step.

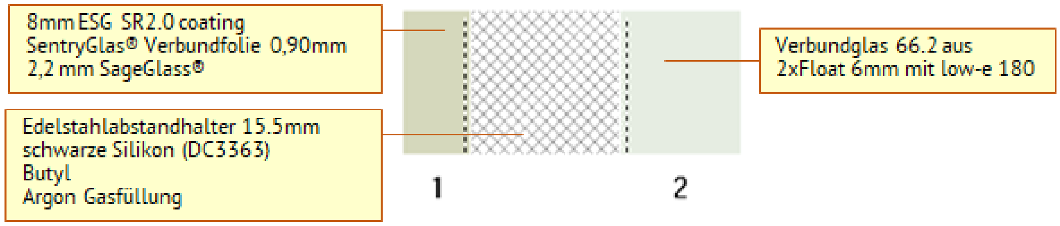

FIG. 3 Glazing system configuration in LBNL Window software

EC Glass States	SHGC	T vis	T sol	Shading ID
Clear	0.437	0.448	0.297	1
Low tinted	0.191	0.121	0.071	2
Medium tinted	0.135	0.040	0.023	3
Fully tinted	0.078	0.007	0.004	4

TABLE 1 Electrochromic glazing center-of-glazing properties (Sage Glass) and shading IDs

2.3 SIMULATION SETUP

The construction properties of the thermal zone are defined as shown in Tab. 2. The 3D geometry of the room with overhang and the columns is also defined in the building file (.b18) as one thermal zone.

The internal gains for four occupants are assigned based on the office occupancy schedule (8:00 to 18:00 for Monday to Friday, and Off for Saturday and Sunday). For electric lighting, 4 LED luminaires (50[Watt]) in 2 different control groups (G1 close to the window, G2 far from the window) were defined. The lighting has a daylight- dependent control in TRNSYS which has a continuous dimming and an on/off function (Type 4) based on the pre-calculated illuminance values in Radiance and the 1st ill setpoint (500 [lx]) and 2nd ill setpoint (250 [lx]).

The infiltration of the building is assumed 0.1 [ACH]. Moreover, for four occupants during working hours, 1.45 [ACH] for hygienic ventilation was applied. To compare the impact of the facade system on energy demand, an ideal heating and cooling system was applied with 27°C for the cooling setpoint and 20°C for the heating setpoint. In this study a wider dead band was used in order to show the impact of shading system clearly. However, the optimal setpoint dead band and its impact on proposed algorithm can be investigated separately.

To calculate local predicted mean vote (PMV) (ISO 7730:2006-05; ASHRAE 2013) in TRNSYS and evaluate thermal comfort, Clothing factor: 1 [clo], Metabolic rate: 1 [met] and Air velocity: 0.1 [m/s] were assumed over the year. Local PMV involves the mean radiant temperature (MRT), which is calculated in the TRNSYS detailed 3Dmodel based on the view factors and the position of occupants (comfort sensors) within the thermal zone. TRNSYS gives a rough approximation of the actual MRT within the zone without considering the posture and body shape of occupants (Ganji Kheybari A. et al. 2018). It is commonly used for building simulations to evaluate the level of thermal comfort.

Construction	Total thickness [m]	U-Value [W/m².K]	Category / Position
Floor	0.42	0.22	Boundary
Ceiling	0.31	0.58	Boundary
Internal Wall	0.13	0.32	Boundary / East and North
External Wall	0.41	0.19	External / South and West

TABLE 2 Construction properties of the thermal zone

Internal Gains	Nr.
People, Seated light work	4
Computer	4
Electric lighting	4

TABLE 3 Internal gains

3 SIMULATION BASED CONTROL STRATEGIES

This paper proposes a way to explore and rank the simulated results of solutions for every time step in order to establish a control strategy for operating the dynamic facade over a year.

3.1 PARAMETRIC SIMULATION RUNS

At the first step, all the possible states of the facade were simulated by using Radiance to get the vertical (E_v) and horizontal illuminance (E_h) hourly values and generate some HDR images. Also the thermal comfort (local PMV) and energy demand values (Q heating, cooling, and electricity for artificial lighting) were calculated in parametric runs of TRNSYS while the air temperature was kept within acceptable range. In these parametric runs, all the building geometries and construction properties are kept constant but the window states.

3.2 RANKING PROCEDURE

In the second step, in order to evaluate the hourly annual results and rank the possible cases, certain criteria were defined to be achieved at every timestep. Then a weighted penalty function is applied (Eq. 1) and when the required performance in the room is not fulfilled, the algorithm rejects the unacceptable case by applying relative penalties. For visual discomfort daylight glare probability (DGP) index, useful daylight illuminance at every workplace, and the usage of electric lighting were taken into account to define the penalties as P_{dgp}, P_{ill}, and P_{elc} respectively. Thermal discomfort penalty as P_{tc} was also defined based on the local PMV index, and energy demand penalty as P_{en} was considered the sensible energy demand at every timestep. Finally, every component can have different priority for the users during the operation (or design) which can be set separately with different weighting coefficients (W_1, W_2, and W_3). These static coefficients influence the ranking procedure and the final outcome.

$$P_{total} = W_1 \times (W_{1\text{-}1} \times P_{dgp} + W_{1\text{-}2} \times P_{ill} + W_{1\text{-}3} \times P_{elc}) + W_2 \times P_{tc} + W_3 \times P_{en}$$

(Eq. 1 Ganji Kheybari A. et al. 2018)

By ranking all possible cases at every timestep, the most appropriate states (top ranked with minimum total penalty) can be found. Repeating this procedure for a complete year (8760 hours) can generate some annual scenarios (time series of selected window states for top, middle, and bottom) that have the best performance (top-ranked scenarios).

3.3 RE-RANKING PROCEDURE

Because of the thermal inertia in the building, the selection of one window state influences the energy demand and thermal condition of the coming time step. This is crucial especially for buildings with large windows and a significant amount of thermal mass (heavy construction material or layers with high capacity for thermal storage). For only lighting parameters, since there is no memory dependency, it is sufficient to check the pre-calculated data for selecting the best performance. However, selecting the top ranked scenarios based on the pre-calculated thermal and energy results does not allow us to consider the thermal memory impact.

In order to avoid this shortcoming in ranking procedure, the top-ranked scenarios are evaluated again and re-ranked through sequential TRNSYS simulation runs. These simulations have a determined duration (StartTime = T - Duration and EndTime = T). The same condition (window states) was applied in all models for past time steps (ts < T) and it is only at the last time step (ts = T) that the algorithm assesses different states for window to find out the best performance. For this purpose, a special dck file template was defined for the series of TRNSYS simulations. After running all the simulations for the course of the year (8760 hours), the final output (Final Scenario) is generated as an annual profile of the most appropriate window states which have the best-simulated performance. This profile can be used later to control the dynamic facade effectively by considering both energy saving and comfort.

3.4 PARAMETERS FOR PERFORMANCE EVALUATION

As previously mentioned, to define the penalty function some parameters and criteria were considered in this study. These parameters are defined below:

- Glare: To predict glare, the enhanced method (Wienold et al. 2006) was implemented by using the calculated vertical eye illuminance (E_v) in Radiance when direct radiation does not hit the observer's eye and evaluating the fisheye HDR images based on the view direction of the occupant and using the Evalglare tool (Wienold, 2004) when the sun is visible to the user´s eye. The final annual results were generated by combining the E_v-driven DGPs and the Evalglare results (based on the simulated HDR images) for every window combination. For this study, we assumed 0.38 as the upper threshold of DGPs, and any case with a DGPs value above the threshold gets a penalty.
- Available daylight: Following the concept of Useful Daylight Illuminance (UDI) (Nabil & Mardaljevic 2005), this paper assumed useful daylighting (E_h) between 300 [lx] and 3000 [lx] at a height of 75 cm. Since there is a significant risk of glare or overheating for the values above the upper threshold, a penalty is applied for the cases outside the acceptable range.
- Electric lighting: By using the daylight-dependent lighting control in TRNSYS, the pre-calculated values (E_h) were used as inputs to calculate the artificial lighting. In order to increase the daylight availability in the building (and reduce the use of electric lighting as much as possible), the case gets a penalty based on the dimming fraction value.
- Energy demand: Based on the set point temperatures in thermal zone that were assigned for heating and cooling (respectively 20 and 27 °C), energy demand (Q sensible) is calculated to keep the room temperature within the assigned range. This range can be defined in many different ways

considering the adaptive thermal comfort. Generally, switchable windows can harvest solar energy in winter time and avoid overheating in summer time. Therefore, this study considered the Q sensible equal to zero (balanced case; when no cooling or heating energy is necessary) as the best situation (no penalty). And for the cases with cooling demand, relatively bigger penalties and for the cases with heating demand relatively smaller penalties were applied.

- Thermal comfort: Even though the room temperature is kept within acceptable range, the impact of the facade on the occupants needs to be evaluated by a local PMV, which considers the occupant's specific position. We assumed that a satisfying thermal condition can normally be achieved when the PMV values are between -1 and +1, which is why a penalty is applied for the cases lying outside of the satisfying range.

3.5 SIMULATION BASED CONTROL, PENALTY FUNCTIONS (P1 AND P2)

By using different weight coefficients in the main penalty function (Eq. 1), the ranking procedure and the outcome will be different. For instance, by setting the coefficient for any component as zero we can eliminate its influence; and by using a higher weight for any parameter, its impact on the total penalty function will be increased. In this study, two different penalty functions were defined to compare with conventional control strategies.

In penalty function number 1 (P1), the ranking algorithm considers visual comfort by taking into account all three aspects of glare, sufficient daylight, and the use of electric lighting. Since glare can be more important in dissatisfying users, this penalty function used the weighting coefficient 2 for glare and 1 for the other aspects of visual comfort. In this function, thermal comfort and energy savings were equally considered to calculate the total penalty. In penalty function number 2, the algorithm considers glare (only), thermal comfort, and energy saving equally. The penalty function number 1 and 2 are shown in Tabel 4.

Controls penalty function	Visual discomfort	Glare	Available daylight	Electric lighting	Thermal discomfort	Energy demand
	W1	W1-1	W1-2	W1-3	W2	W3
number 1 (P1)	0.25	2	1	1	1	1
number 2 (P2)	1	1	0	0	1	1

TABLE 4 Simulation based control, penalty functions (P1 and P2)

4 CONVENTIONAL CONTROL STRATEGIES

This paper investigates the impact of using the proposed simulation based control by comparing the annual results with other conventional control strategies. The Baseline is the clear state of the EC glazing window with the SHGC of 0.437 without using any sun protection system (NoCtrl). Also in order to show the maximum impact of the shading system on cooling demand, the annual results of always fully tinted window (CtrlDark) are calculated.

Another control was defined to protect occupants against direct sun glare (CtrlDirSun). Whenever the sun is visible to one of the occupants in the room, the shading system will be medium tinted (SHGC = 0.135), otherwise it will be clear. For radiation-dependent shading control, two different controls were used. The 2 state (clear/dark) control (CtrlRad1) depends on one threshold; if the direct radiation on the window surface (IB_Win) is higher than 50 [W/m²] it will be medium tinted (SHGC = 0.135). The four state (clear/dark + 2 intermediary states) control (CtrlRad2) depends on different thresholds of direct radiation. When radiation is higher than 50, 100, and 150 [W/m²], the shading will be tinted in 3 different steps (low tinted, medium tinted, and fully tinted).

For all the controls, the bottom zone of the window was kept clear in order to provide enough diffused daylight into the room, while the shading can still protect the occupants from direct sunlight on the upper and middle zones.

5 RESULTS

In order to investigate the impact of the proposed control strategy, all the controls for EC glazing were applied to the defined office room model in TRNSYS over a year (0 - 8760 hr, continuously) and the results are showed in Tab. 5. The same simulation setup, boundary conditions, and dead band for set temperature (20°C to 27°C) was used for all simulations.

The annual cooling demand (Q cool [kWh/m²a]) in blue, annual heating demand (Q heat [kWh/m²a]) in red, and total annual electricity demand for lighting (elec Light [kWh/m²a]) in yellow are depicted for all control strategies in Fig. 4 left.

Additionally, Fig. 4 right shows the annual thermal comfort (PMVs) for every user by calculating the percentage of occupied hours with dissatisfying thermal conditions. We assumed the hours with local PMV>+1 or PMV<-1 dissatisfying hours. The total number of occupied hours is 2610 in this study. Reducing the percentage of the hours in a year with dissatisfying thermal comfort shows the improvement in thermal condition in the room by using proposed control (P1 and P2).

To assess the impact of the control strategies on avoiding glare over a year, the percentage of occupied hours with disturbing and intolerable glare (when DGP ≥ 0.38) was calculated (Fig. 5 left). In addition, providing the useful daylight in the room should be evaluated over the year by calculating the percentage of occupied hours with useful daylight when illuminance is between 300 [lx] and 3000 [lx]. Fig. 5 shows the impact of the different control strategies on visual comfort.

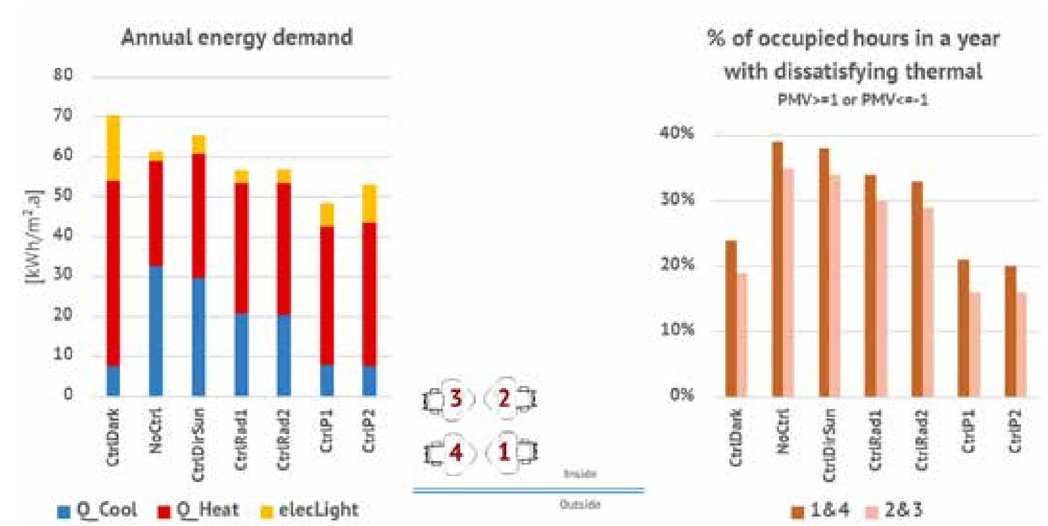

FIG. 4 left: The annual energy demand [kWh/m^{2}a], right: The percentage of occupied hours with dissatisfying thermal comfort for all controls.

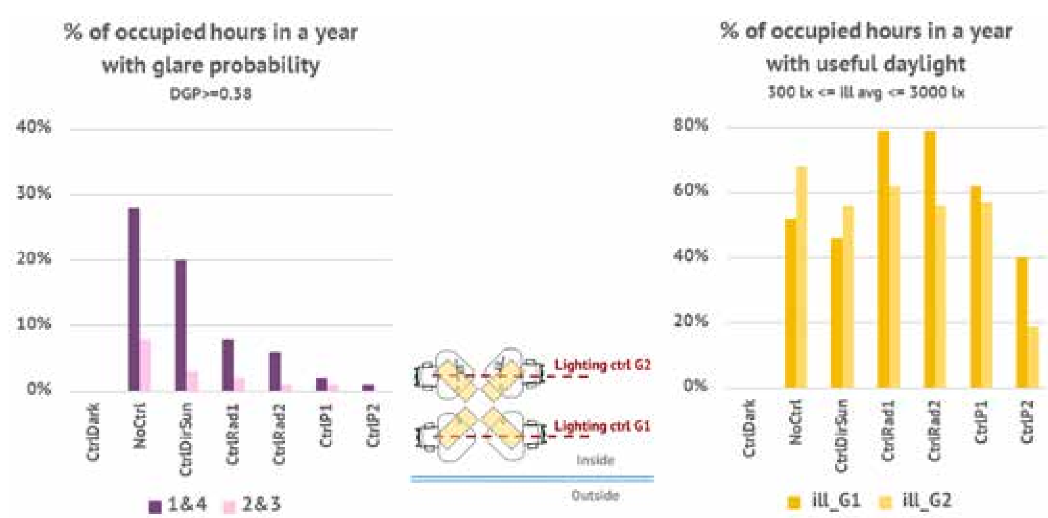

FIG. 5 left: The percentage of occupied hours with glare probability, right: The percentage of occupied hours with useful daylight.

	Annual Energy demand kWh/m^2.a			% of the occupied hours PMV >= 1 or PMV <= -1		% of the occupied hours DGP >= 0.38		% of the occupied hours 300 lx <= ill <= 3000 lx	
	Q_Cool	Q_Heat	elecLight	1&4	2&3	1&4	2&3	ill_G1	ill_G2
CtrlDark	7.5	46.6	16.3	24%	19%	0%	0%	0%	0%
NoCtrl	32.6	26.3	2.5	39%	35%	28%	8%	52%	68%
CtrlDirSun	29.7	31.2	4.7	38%	34%	20%	3%	46%	56%
CtrlRad1	20.7	32.7	3.3	34%	30%	8%	2%	79%	62%
CtrlRad2	20.3	33.1	3.5	33%	29%	6%	1%	79%	56%
CtrlP1	7.8	34.8	5.9	21%	16%	2%	1%	62%	57%
CtrlP2	7.6	35.9	9.6	20%	16%	1%	0%	40%	19%

TABLE 5 Annual simulation results for different controls

6 DISCUSSION

By considering the annual energy demand of the building with no shading control (NoCtrl) as the baseline, Fig. 4 left shows that control for direct sun glare (CtrlDirSun) slightly reduced the cooling demand (9%, mainly during the winter time with the high risk of glare and overheating) but increased the electric lighting demand. Both radiation-dependent controls (CtrlRad1 and CtrlRad2) reduced the cooling demand (36% and 38%).

Control strategies based on the penalty functions (P1 and P2) both improved the energy performance of the building by reducing the cooling demand (76% and 77%), at the cost of increasing the electric lighting and heating demand. Since the penalty function number 2 (P2) only focused on glare and not providing useful daylight, the results shows the higher demand in electricity for lighting. Results show 5.9 [kWh/m²a] electric lighting for P1and 9.6 [kWh/m²a] for P2. Fig. 4 right shows that by using the proposed control strategies (P1 and P2) thermal condition was improved and the percentage of occupied hours with dissatisfying thermal comfort was reduced below 20%. Even though, this 20% is still too high regarding some standards, the improvement in thermal comfort is only achieved by controlling the facade while a wide range of dead band (20°C to 27°C) was used for controlling the active heating and cooling systems. The authors did some other studies and by reducing the size of dead band providing comfortable indoor condition is totally achievable.

In Fig. 5 one can see that both radiation-dependent controls (CtrlRad1 and CtrlRad2) and control strategies based on the penalty functions (P1 and P2) were able to significantly protect the occupants from discomfort glare. However, proposed controls P1 avoided glare more effectively by providing more useful daylight for the users at the same time.

7 CONCLUSION

By using the proposed simulation based control strategy for EC glazing (P1 and P2), all aspects of visual and thermal comfort as well as energy saving (specially on reducing the cooling demand and electricity for lighting) can be taken into account for optimizing. As long as the users have an index for any other performance such as view to the outside, color rendering, CO_2 emission, ..., those performances can be also considered in this method by adding new components and associated weighting fractions in the main penalty function. In addition to finding the optimum control, this method can be applied to design any performance driven dynamic façade such as dynamic shadings, fitted ETFE cushions, ...

The results of this study for optimum EC window states are based on the specific climate, building geometry and properties. But the simulation based method can be generally used for any climate, geometry, and construction type. Moreover, some of the applied methods in the proposed framework make it easier to repeat the procedure for another climate or geometry. For example, using matrix based method for lighting simulations which are the bottle neck of any building optimization process, it is possible to replace only the sky matrix based on the new weather data and use the rest of previous matrices. Despite the promising anticipated benefits of a dynamic façade such as EC which can be assessed through the proposed framework, the application of this method in a real building is still limited, due to the real-time rapid changes in sky condition and user behaviors and preferences. Addressing to those shortcoming, weather forecast and user's feedback should be considered in a real-time decision making algorithm.

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Optimization of Twisted Vertical Louvers Based on Artificial Neural Networks

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Abstract
Since indoor illumination plays a significant role in the physical working environment, it is crucial to make good use of daylight in the design process of buildings. However, high level indoor delighting often goes along with discomfort glare and excessive heating. Thus, an advanced vertical louver system is designed to address this problem. The twisted vertical louver is composed of a set of flexible strips, it can be half open, and half closed when the upper and lower control rods of the strips rotate in different angles. Optimizing the design parameters of the strip can significantly enhance the advantages of such kind of louver: reducing glare, providing a view outside, and ensuring a relatively bright daylighting. The conventional optimal search method relies on a large number of samples for an exhaustive search. However, the climate-based dynamic simulation of Daylight Factor (DF) and Daylight Glare Probability (DGP) is time-consuming for even a single simulation sample. Thus, it is hardly possible using such a method to optimize the daylighting performance of the twisted vertical louvers accurately. To address this problem, this study uses an optimization algorithm - Artificial Neural Networks, combined with daylighting performance simulations, to determine the optimal design parameters of the proposed louvers with multiple objectives.

Keywords
glare, daylighting, view, neural network, regression, optimization

1 INTRODUCTION

With the improvement of living standards, people call for a higher quality of the physical working environment. Especially in the aspect of indoor illumination, the daylighting level has a great influence on the satisfaction and productivity of the users [1]. Thus, it is crucial to make good use of daylight in the design process of buildings. However, the mass of day-light availability usually goes along with discomfort glare and excessive heating [2]. Vertical louver system is commonly used to reduce the excessive heating and discomfort glare.

In the meantime, it allows partial diffuse light to enter the room and ensure a qualified indoor illumination. However, the conventional vertical louver system is unable to achieve an effect of partial shading and partial daylighting, as its single strip is rarely to be half open and half closed [3]. Thus, in some circumstance, using a vertical louver system may lead to an insufficient indoor daylighting or discomfort glare within the field of view.

To address this problem, an advanced twisted vertical louver system is proposed in this study. The twisted vertical louver system is composed of a set of flexible strips. When the upper and lower control rods of the strips are rotated by different angles, the louver system can be partially open and partially closed. This feature provides a possibility for making maximum use of daylighting and avoiding discomfort glare. Whereas, determining the optimal size and twisted form of the strips is still a challenge, as it involves the trade-off between the indoor daylighting, glare and view field.

Therefore, this study mainly focuses on the optimization of the dimension, twisted angle and middle control rod of a twisted vertical louver system applying outside the south-facing facade of an office cell.

Regarding the previous studies on the optimization of shading devices, many researchers used the enumeration method to seek out the better-performed solutions among a series of investigated cases [4][5]. For example, Jeong Tai Kim et al. conducted a set of daylighting experiments to find the most appropriate depth of an external shading device [6]. M. David et al. Compared the thermal and visual effects of four types of shading devices to determine the best-performed one [7].

In the last two decades, with the development of interdisciplinary research, many studies have been conducted to combine the optimization algorithms and simulation tools in the area of building performance optimization [8][9][10][11]. Cristian Lavin et al. carried out a series of simulations to get an optimal perforated screen. The evolutionary algorithms embedded in Galapagos was used to balance the improvement of Useful Daylight Illuminance (UDI) and the reduction of Daylight Glare Probability (DGP) [12]. Michela Turrin adopted the ParaGen to combine parametric modeling, performance simulation software and genetic algorithms [13]. Yu et al. proposed a simulation-optimization tool by using the GA-BP network, which was able to optimize the building performance during the building design process. In this way, they tried to find the trade-off between thermal comfort and energy consumption [14].

The currently common optimization methods as mentioned above mainly rely on an optimization tool plugged into the parametric modeling software. The advantage of these methods is that they can conduct simulation and optimization simultaneously, and easily visualize the optimization process in the modeling interface. However, in this study, the simulation of daylighting and glare is extremely time-consuming. While the iterations for an accurate optimization require a considerable amount of simulations for the training set. Therefore, an optimal method is required to ensure a more independent and efficient optimization process for such kind of time-consuming cases.

In this study, deep neural networks and advanced machine learning approaches are adopted for the optimization. Instead of conducting the simulation and optimization simultaneously, the whole optimization process is carried out in three separate steps, which are simulation, regression, and optimization. The advantage of this method is that the daylighting performance simulation process for the training set can be conducted on several servers parallelly. Accordingly, the simulation time can be reduced significantly. Besides, the operation mistakes or breaking off can be easily rectified during the simulation process, which, therefore, ensures a more accurate optimization result. Furthermore, this study also investigates how the weights for different evaluation indicators affect the final optimization results.

2 METHODOLOGY

In this study, an office room in Guangzhou, China (latitude 23.23°N and longitude 113.26°E) is used as a case study to test and optimize the proposed method. The study process consists of the following steps:

Simulation: a parametric model of the room is built in Grasshopper, shown in Fig. 1 Moreover, as can be seen in Fig 1, the twisted vertical louvers are applied on the façade of the room. The variables include the width of the louver strip (namely a), the rotation angle of the upper control rod (namely b), rotation angle of the lower control rod (namely c), and the height of the middle control rod (namely d).

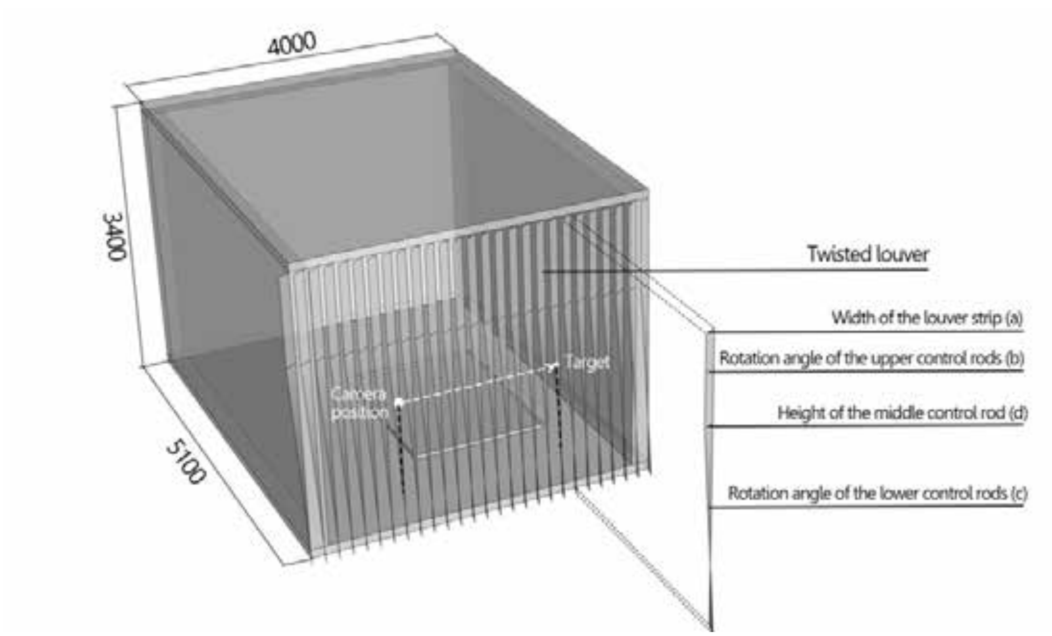


FIG. 1 The dimension of the south-facing office geometry and definition of each indicator

The simulation tools mainly contain Grasshopper, DIVA, and Python. DIVA grasshopper is used to simulate the Daylight Factor (namely x) of the room at a working plane height, Daylight Glare Probability (namely y) at the sitting viewpoint near to the window. The view (namely z) is determined as the ratio of the shortest distance between two adjacent louver strips and the distance from the louver strips to the viewpoint (Fig 2). For the simulation of the Daylight Factor, a grid plane is set at the height of 800 mm above the floor, and the grid size is 10 mm. To simulate the DGP, a view point is set at the height of 1200mm, and it is 500 mm away from the window. Python program is inserted to establish an automatic input and output loop for a constant simulation. The settings of room surface materials are shown in Tabel 1.

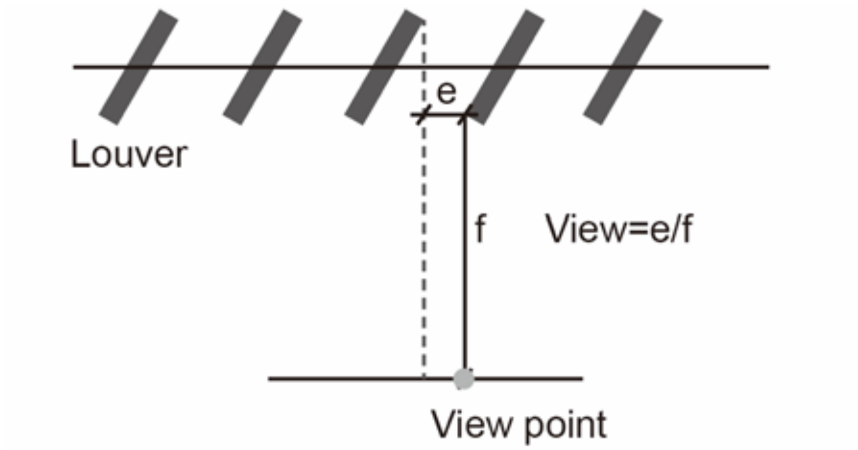


FIG. 2 Definition of view

Surface	Ceiling	Window	Floor	Interior wall	Louvers
Material	Generic ceiling	Standard clear double glazing	Generic floor	Generic wall	fabric
Reflectance	80%	-	20%	50%	30%
Transmittance	0	80%	0	0	0

TABLE 1 Text room surface materials and parameters settings

Neural network regression

Based on the simulation results, an Artificial Neural Networks (ANN) regression model is trained to fit all the values of u and v for any combination of a, b, c and d. The regression model is a network, containing six layers. The first three layers consist of 256 nodes, while the last three layers consist of 512 nodes. RELU (Rectified Linear Unit) is used as the activation function. In order to balance efficiency and accuracy, a series of experiments are conducted to determine the appropriate hyperparameters. The loss function is shown as Function1.

$$\text{Regression loss} = (x_{pred} - x_{true})^2 + (y_{pred} - y_{true})^2 \quad (1)$$

Where, x_{pred} is the predicted value of x by the regression model,

x_{true} is the simulated value of x by DIVA,

y_{pred} is the predicted value of y by the regression model,

y_{true} is the simulated value of y by DIVA,

The optimization algorithm is SGD (Stochastic gradient descent). In the training process, the learning rate is 0.01, at a learning rate decay of 0.9 per 10,000 steps. The threshold for the end of training is set to 1e-6. In this study, order counts, when counting the combinations of the a, b, c and d. The inputs of a, b, c, and d are transferred into another four equivalent values, and each of them is normalized to a value between 0 and 1, using Functions 2 to 5.

$$\tilde{a} = \frac{a}{300} \quad (2)$$

$$\tilde{b} = \frac{b}{90} \quad (3)$$

$$\tilde{c} = \frac{c}{90} \quad (4)$$

$$\tilde{d} = \frac{d}{1000} \quad (5)$$

Where, 300, 90, 90 and 1000 are the spans of a, b, c and d, respectively. The simulation results are the base for the regression. 80% of the simulation results are selected randomly for the training set, while 15% of them for the test set, and 5% of them for the validation set.

Neural network optimization

ANN is also applied to the optimization process. The whole optimization process can be divided into two stages, which are the inference stage and the back-propagation stage. In the first stage, the inputs are the optimal values selected from the simulation results. Based on the inputs, the network calculates the outputs. In the second stage, the input values are updated based on the gradient propagated through the network. The network structure and weights are the same with those for the process of regression. The input values are expected to approach the optimum value gradually.

The following is the optimization function (Function 6):

Based on this function, a smaller overall score indicates a better optimization result. The overall performance of and the total optimization time-consumption are assessed to validate and optimize the optimization process.

$$\text{Score}_{\text{overall}} = w_y \text{Score}_y + w_x \text{Score}_x + w_z \text{Score}_z \quad (6)$$

$$\text{Score}_y = \left(\frac{y - y_{min}}{y_{max} - y_{min}}\right)^2$$

$$\text{Score}_x = \left(1 - \frac{x - x_{min}}{x_{max} - x_{min}}\right)^2$$

3 RESULTS

The simulation runs a total of 423 models. The results of simulation DF and DGP can be used for the regression and optimization.

Regression results

The training ends after 420,000 steps, where the training loss is 7e-4 (less than1e-5). Tab. 2 shows part results of the test set. As can be seen from the results that the difference between the simulation and neural network regression results are less than 0.01, which indicates a relatable regression performance.

a	b	c	d	X_{true}	Y_{true}	X_{pred}	Y_{pred}
50.025	59.969	44.986	999.100	3.24	0.327722	3.246204	0.328659
149.984	44.986	74.946	999.100	3.19	0.335090	3.196169	0.334877
249.865	15.006	44.986	399.939	3.26	0.336288	3.269616	0.335960
299.775	44.986	44.986	200.059	6.01	0.336429	6.057541	0.337187
149.984	89.919	44.986	999.100	3.35	0.324133	3.359800	0.324065

TABLE 2 The predicted values and simulated values of x and y for different combinations of a, b, c and d.

Optimization Results

After a series of simulation, groups of optimal solutions are achieved according to different settings of wx, wy, and wz. Typical sets of results are selected to do further analysis and discussion.

WEIGHT			OPTIMUM RESULTS				PERFORMANCE			SCORE			
Wx	Wy	Wz	a	b	c	d	x	y	z	x	y	z	overall
0.33	0.33	0.33	299.78	0.01	89.92	397.88	4.45	0.4	0.34	0.03	0.42	0.19	0.22
Visualization and simulation verification							 Simulated DGP=0.37						

TABLE 3 Optimization result of case 1.

In the optimization of this case, it shows that when all the three weights are set to 0.33, the optimal values of x, y, z are 4.45, 0.4, 0.34 respectively. Though none of the indicators achieves the best value, each of them guarantees a relatively good performance, and thus lead to a balanced performance when considering the daylight, glare, and view simultaneously. Moreover, a little deviation can be seen between the optimal results (0.4) and simulation results (0.37).

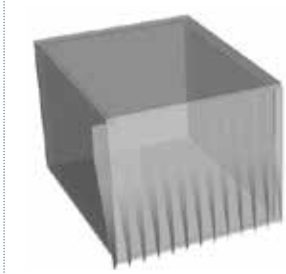
WEIGHT			OPTIMUM RESULTS				PERFORMANCE			SCORE			
Wx	Wy	Wz	a	b	c	d	x	y	z	x	y	z	overall
0.4	0.4	0.2	299.78	0.01	59.61	810.41	4.18	0.33	0.14	0.06	0.19	0.58	0.21
Visualization and simulation verification							 Simulated DGP=0.32						

TABLE 4 Optimization result of case 2.

In the optimization of case 2, the weight value of x and y are relatively high, while the smallest one is assigned to z. Thus, DF(u) and DGP(v) are considered to be the most important factor in this optimization. The results in Tab. 4 show that the optimized DF value is 4.18, DGP value is 0.33, and the corresponding scores are 0.06 and 0.19 respectively. For the view, the reduction of optimal value Z is greater than 50% compared with that in case1, the value of this indicator is only 0.14. Thus the corresponding score of z is fairly high.

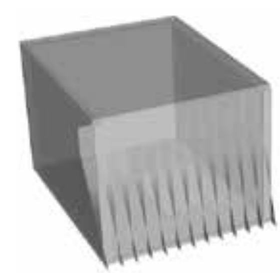
WEIGHT			OPTIMUM RESULTS				PERFORMANCE			SCORE			
Wx	Wy	Wz	a	b	c	d	x	y	z	x	y	z	overall
0.2	0.4	0.4	299.78	0.01	89.92	624.97	3.06	0.36	0.31	0.19	0.27	0.23	0.24
Visualization and simulation verification							 Simulated DGP=0.36						

TABLE 5 Optimization result of case 3.

In the optimization of this case, the greatest weight value (0.4) is given to y and z. The weight for x is 0.2. Accordingly, the DGP (y) and view field (z) is the major concern in the optimization of this case. The results in Tab. 5 show that the DF is much lower than that in case 2, which is only 3.06, and the corresponding score is 0.19. The value of the view field is almost twice as much as that in case 2, reaching 0.31, and the corresponding score drop dramatically compared with the score in case 2. The value of DGP (y) remains almost the same in these two cases, which is 0.36.

WEIGHT			OPTIMUM RESULTS				PERFORMANCE			SCORE			
Wx	Wy	Wz	a	b	c	d	x	y	z	x	y	z	overall
0.4	0.2	0.4	299.78	89.92	89.92	628.41	5.71	0.46	0.57	0	0.72	0	0.15
Visualization and simulation verification							 Simulated DGP=0.46						

TABLE 6 Optimization result of case 4.

In the optimization of case 4. DGP (y) is considered as the less important factor, which is 0.2. The weight of the other two factors is the same. The results in this simulation show that the optimized DF(x) value is 5.71 and view field(z) is 0.57; these two values are almost twice as much like that in case 3. The corresponding scores of these two factors are 0, which means these two indicators reach the best performance among all results.

4 CONCLUSIONS

This paper investigates a multi-objective parametric optimization method for the twisted vertical louvers on the south-facing offices. The optimization process is embedded in deep neural networks in this study. The results show that the differences between the simulation and the neural network regression results are less than 0.01. It means that deep neural networks can achieve a reliable regression performance. Moreover, weights have a significant effect on the optimization results. Appropriate weight values must be determined based on the specific requirements of the users.

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Parameters to Design Low-Tech Strategies

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Abstract

"Low-Tech" is the new "High Tech"; this statement is the current core subject in European architecture. In the last 25 years, technical equipment and controlling systems were implemented in buildings to save energy and create comfort. The challenge of how to design and construct buildings for a post fossil century was rather tackled with (additional) high performing supply systems than architecture itself. However, building examples show that the expectations on both energy efficiency and thermal comfort were not fulfilled while the complexity of design and operating process increased steadily.

As a reaction, initial building projects were focused on reducing technical systems to an absolute renunciation of the main components of active building systems. One example, the office building 2226 by be architects in Lustenau, Austria was designed to become a showcase for a maximised passive building strategy. However, there are open questions about the general transferability of this building strategy: Fundamental statements concerning winter and summer indoor comfort, embodied energy of the construction, and temporary load peaks are disregarded in the debate.

In order to contribute to the closing of this gap, a parametric analysis was carried out at the Technical University of Munich, at the Chair of Building Technology and Climate Responsive Design. The study is part of Elisabeth Endres´ PhD Thesis regarding the interface of architecture and technical systems. Using the thermal dynamic building simulation plug-in TRNLizard in Rhinoceros 5® and Grasshopper®, the potentials and consequences of passive building strategies are evaluated. The results regarding to the quality of the façade show, that winter conditions and an ongoing optimization of the building envelope to reduce heating loads is not the issue for the future. Especially the summer conditions will significant influence the design of the buildings, especially against the background of generally increasing climatic conditions and head island effects in the cities. An also important conclusion is that even the implementation of only one technical system creates a high degree of robustness with regard to the indoor climate conditions in the room. It turns out that the further question is not the optimization of all passive components, it is more to define the robustness of the systems to be able to develop durable buildings, which withstand uncertain boundary conditions.

Keywords

Low-Tech, robustness, building envelope, indoor comfort, energy efficiency, embodied energy

1 INTRODUCTION

The building envelope represents the interface between outside and inside climatic conditions. Its performance is essential for the comfort of occupants.The facade as the generator of heat and cooling loads is the most responsible element for the necessary amount of technical systems in our buildings. Apart from this, the building envelope is part of the architecture and communicates to the built and unbuilt environment. In the last 30 years, the question of energy-efficiency and indoor comfort was answered with High-Tech solutions concerning all parts of building design. The implementation of technical supply and automation systems in buildings to save energy and to increase comfort has been mirrored in the facade and general building design of many buildings. Research, technological development, and the growing industry make nearly all geometries in designing, construction, and supply possible. Building services nowadays meet desired requirements regardless of outside climate, embodied energy and different lifecycles of the construction.

Through the research and development of new materials and systems, the performance and the efficiency of buildings increased in both directions: passive and active. One result is the rising complexity of the planning process, the other result is the complexity of building operation and maintenance. Monitoring measurements show that the energy performance of those buildings is below an acceptable level. Regarding traditional architecture based on Low-Tech strategies - for example in the Mediterranean context or in subtropical climate regions – such buildings are still working with less technical equipment. Therefore, we must question the current standards and planning processes.

Five years ago, the building 2226 in Lustenau, Austria, designed by be architects started the currently ongoing 'High-Tech versus Low-Tech' discussion. This building is working without any mechanical ventilation or active water-based conditioning system (Eberle et al., 2016). Different attitudes and statements about this pilot project were discussed since it has been published. However until now, the answer about right or wrong within the range of 'maximum passive' and 'no active' is not given up. There are still fundamental questions and different positions about the definition of Low-Tech.

- Does Low-Tech has the same meaning as 'No-Tech'?
- Is Low-Tech a definition for the robustness of a building in case of changing boundary conditions?
- Based on the context of robustness: Is it more efficient to implement simple technical systems due to unpredictable boundary conditions such as climatic conditions, user behaviour, and system failures?
- What does robustness mean regarding the interaction of the building envelope, building performance, technical supply systems and environmental impact?

These are the main questions of the research work 'Parameterstudie Low-Tech Bürogebäude' (parametric study on Low-Tech office buildings) at the Technical University of Munich, which was published in 2018 (Endres et al., 2018). The aim of this project was to evaluate the performance of different passive and active parameters. The first step was to evaluate a No-Tech-strategy regarding different façade qualities and natural ventilation operations. The second step was to implement three different mechanical systems to improve the impact and the robustness towards orientation, façade qualities, energy efficiency and indoor comfort.

This paper is focused on the results of the parametric study regarding the influence on indoor comfort and energy performance of different passive and active façade parameters. In addition to these considerations, the embodied energy of the different facades was evaluated in the overall project based on the data base ÖKOBAUDAT of the German Federal Ministry of the Interior, Building and Community (Ökobaudat, 2017). The results of this investigation are not part of this paper.

2 METHODOLOGY

The methodology of the study at hand is structured and described in following work packages:

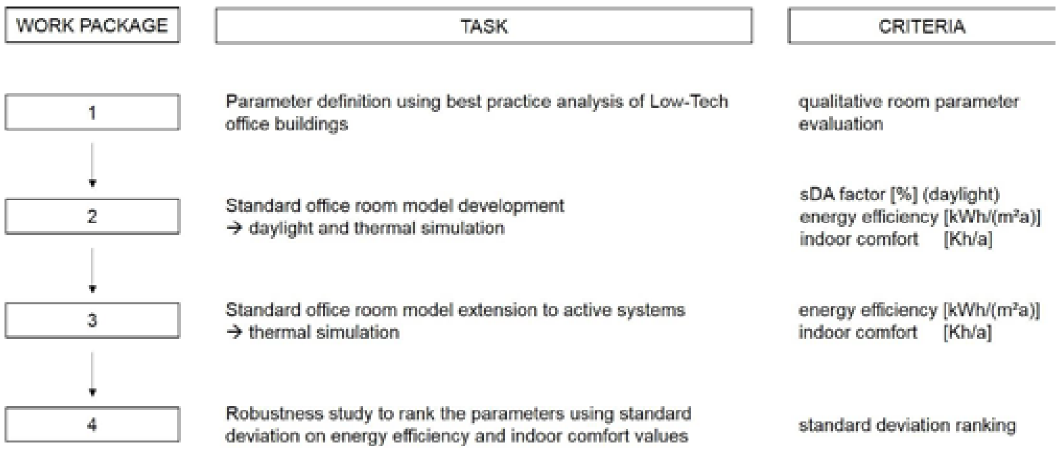

FIG. 1 Methodology scheme

Work Package 1: To identify and to evaluate the potentials of specific parameters, the first step is a best practice analysis. Representative buildings were chosen by their façade designs and implemented technical supply systems. Parameters concerning the construction, the window, the physical character of the envelope, and the boundary conditions of the different supply systems were analysed and categorised. The selected buildings are designed to function as examples for strategies with an innovative approach in the context of energy efficiency – possessing a 'Low-Tech character' or an innovative façade design.

Work Package 2: Based on the results of step 1, a typical office layout was chosen as the general model. Using this standard room model, dynamic simulations of daylight and thermal performances were carried out, generating comparable results regarding the impact of passive parameters.
The daylight data was generated with the dynamic simulation engines Radiance and Daysim, using the plug-in Honeybee in Grasshopper® interface in Rhinoceros® (Grasshopper, 2007) (Honeybee, 2016). For thermal dynamic 3D building simulation, the simulation engine TRNSYS 18 with the plug-in TRNLizard in Grasshopper® / Rhinoceros® was used (TRNLizard, 2014).

Work Package 3: Based on the standard room model, three different active systems were simulated and evaluated in addition to the passive boundary conditions of work package 1. Only one change per scenario and no combinations of different systems were conducted. Again, the core software TRNSYS 18 with the plug-in TRN Lizard to Rhinoceros® and Grasshopper® were used (TRNLizard, 2014).

Work Package 4: Using the mathematical method of determining the standard deviation, the influence of the parameters was expressed as standard deviation concerning the thermal simulation results on heating demand and overheat hours in summer. The deviation values were used to rank the parameters.

3 SIMULATION MODEL, INVESTIGATED PARAMETERS, AND EVALUATION CRITERIA

3.1 SIMULATION MODEL

The basic simulation model is a one zone model with a typical net floor space of a room design in office buildings (Fig. 2, floor plan) with 20.34 m². A clear room height of 3.20 m is set equally for both suspended and non-suspended ceiling cases in order to meliorate indoor comfort using passive strategies (Fig. 2 side views). One external wall with window is connected to outside climate conditions. The room is located between two building floors and neighbored by offices as well as the corridor.

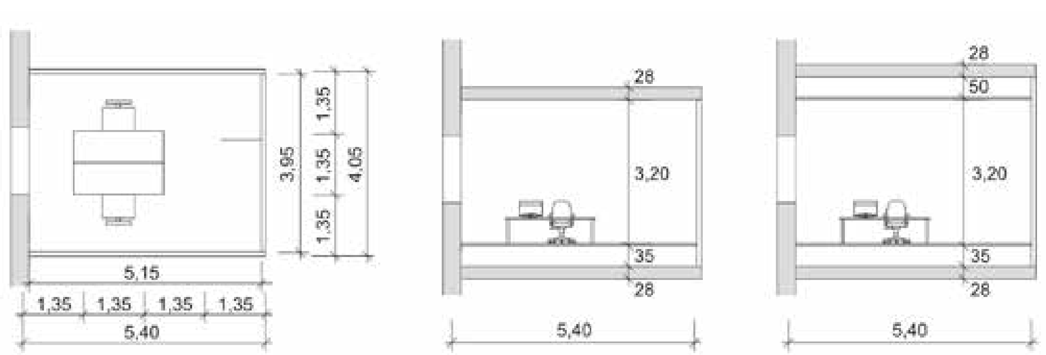

FIG. 2 Standard room model: floor plan, side view, and side view with suspended ceiling (from left to right)

The office room is equipped for two workplaces leading to heat loads of 75 Watts per person, 70 Watts per computer, and 10 Watts per square meter artificial lighting. Occupancy hours are set Monday to Friday, 7 a.m. to 6 p.m. (DIN V 18599-10:2011-12).

3.2 PASSIVE PARAMETERS

This sub-chapter describes the investigated passive parameters that influence the building performance regarding indoor comfort and energy efficiency. The following parameters were identified as being significant to evaluate passive building strategies. The selection of the parameters is based on a best practice analysis of different office buildings and their performance. The most influential factor is the façade and its individual components, which creates the interface between the outside and inside climate. This is also reflected in the specifications in the applicable regulations, e.g. ENEV or the requirements of the certification systems.

Identified façade parameters influencing the passive building performance:

- 4 building orientations: south, east, north and west
- 5 thermal standards of envelope: construction types evaluated regarding embodied energy and energy standards
- 5 U-values: range from 0.28 W/m²K (EnEV, 2014) to 0.15 W/m²K (Passivhaus Institut, 2018)
- window to wall ratio: range evaluated by the daylight simulation
- 2 window types: g-value characterised by the daylight transmission g = 0.50 / 0.26

Identified building design + construction parameters influencing the passive building performances:

- light or massive façade construction: 5 different scenarios
- thermal mass in connection with the indoor environment: 3 different scenarios
- self-shading effect by the wall (reveal depth): 2 different scenarios

The results of a preceding simulation step showed that the indoor temperature in winter falls below 20 °C using natural ventilation for fresh air supply. Due to standards for working places, a heater is provided in all simulations and the effort is evaluated by the energy demand for the system. Considering this aspect, the heater is implemented in all base case scenarios, where only façade and indoor constructions and qualities are varied.

3.3 ACTIVE PARAMETERS

In order to evaluate the building performances in indoor comfort and energy efficiency, active parameters were investigated. In addition to the base case scenarios of passive parameters and heating system, three active components were added and evaluated. Each active strategy contains one technical aspect, no combinations of active parameters were tested.

Simulation scenarios for active systems:

A heater + passive parameters (base case)
B heater + solar screens outside
C heater + mechanical ventilation
D heater + cooling by thermal active ceiling

The base case as well as scenarios b) and d) operate without any mechanical ventilation. Night cooling is considered in all cases.

3.4 EVALUATION CRITERIA

Within the last ten years, efforts to evaluate architecture by creating certification systems such as DGNB®, LEED®, BREEAM® showed the complexity to design and evaluate sustainable buildings. The discussion of Low-Tech strategy evaluation is still driven by individual experience, monitoring results and non-working examples. It is more of an emotionally driven discussion on which validated general statements do not exist. It also needs statements regarding the definition of robustness and the distinction between "Low-Tech" and "High-Tech". Some evaluation criteria are assumed to be more important than others. The authors of the study on hand followed their methodology steps introduced in chapter 2 and identified following evaluation criteria along with each step (see Fig. 1): daylight, energy efficiency, indoor comfort, and embodied energy.

Daylight evaluation: The ambient daylight available is defined as the first restricting factor. The Spatial Daylight Autonomy (sDA factor) describes the share of the analysed room area that shows 300 lx ambient daylight supply in 50 % of the yearly occupied hours. In order for the ambient daylight quality in the room to be rated as 'nominally acceptable', the sDA300,50% must meet or exceed 55 %. In order to be evaluated as 'favorably' supplied by ambient daylight, the sDA300,50% must meet or exceed 75 %. The sDA factor is introduced by the "Illuminating Engineering Society of north America (IES)" and has been an established index for daylight quality since 2012. (sDA, 2012) Accordingly, the sDA range as ambient daylight criterion for the study on hand was defined as:

$$55\ \% \leq sDA300{,}50\% \leq 75\ \% \quad (1)$$

Indoor comfort evaluation: The indoor comfort criterion for winter time is declared 20 °C operative temperature according to the German standards for working spaces. The benchmark for indoor comfort in summer time is set to 261 Kh/a (Kelvin hours per year) during room occupancy according to the standard (DIN EN 15251:2012-12).

Energy efficiency evaluation: To compare different strategies and show the influence of the technical systems, energy efficiency is calculated in kWh/(m2a) electric energy. In case of heating and cooling energy, the system is operated by heat pumps and chillers with an efficiency number (COP) of 4.

4 RESULTS

4.1 DAYLIGHT SIMULATION

The right amount of available indoor ambient daylight is a crucial factor that has to be met in any simulation case before investigating on the influence of further passive and active parameters. Therefore, a daylight simulation was carried out and the variants dropping below the minimum sDA threshold of 55 % or exceeding the maximum sDA threshold of 75 % were filtered out. After the daylight evaluation, 129 façade combinations matched the defined sDA benchmarks. These combinations are called base cases in the following thermal simulations.

4.2 CLIMATE CONDITIONS

To be able to assess the impact of the climate conditions, a preliminary study was made with the current German climate conditions in Potsdam and its metrological prognosis for 2050. The results showed the expected significant impact of climate change. Whereas the passive strategy without any technical supply in consideration of today´s climate meets the requirements of indoor comfort in summer for almost all variants, this is not the case for future climate conditions. To tackle future requirements for Low-tech buildings, all thermal simulations were based on the climate data of the 2050 prognosis. The results showed that the climate is one of the key aspects in the discussion about unpredictable boundary conditions. Therefore, this preliminary study is a significant step in order to define robustness.

4.3 PARAMETRIC STUDY

With the knowledge of the preliminary studies (daylight, climate conditions) the passive parameters were evaluated with and without the additional active systems. The results are shown in point cloud graphs below. The influence of each parameter for scenario a) heater + passive parameters is clearly shown in the respective point cloud graph, e.g. cloud graph for orientation (Fig. 3) and glass quality (Fig. 4).

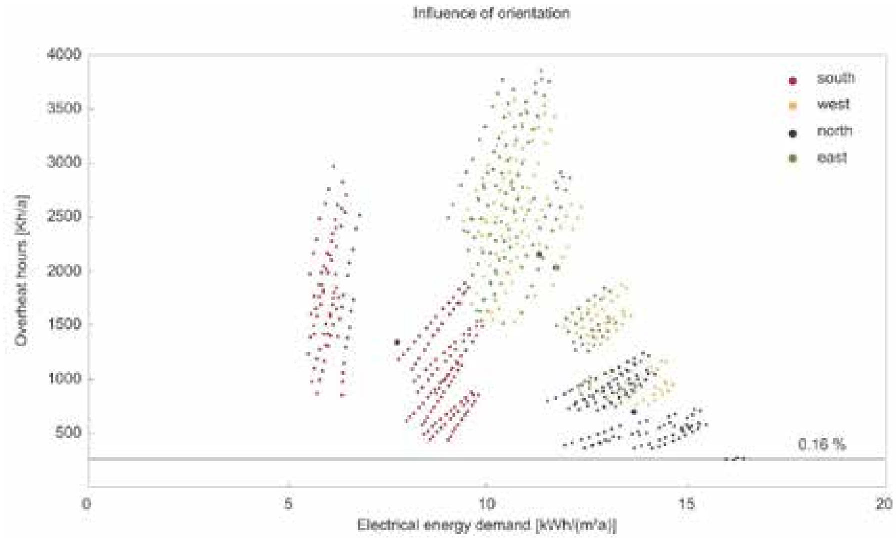

FIG. 3 Scenario A: heater + passive parameters: influence of orientation

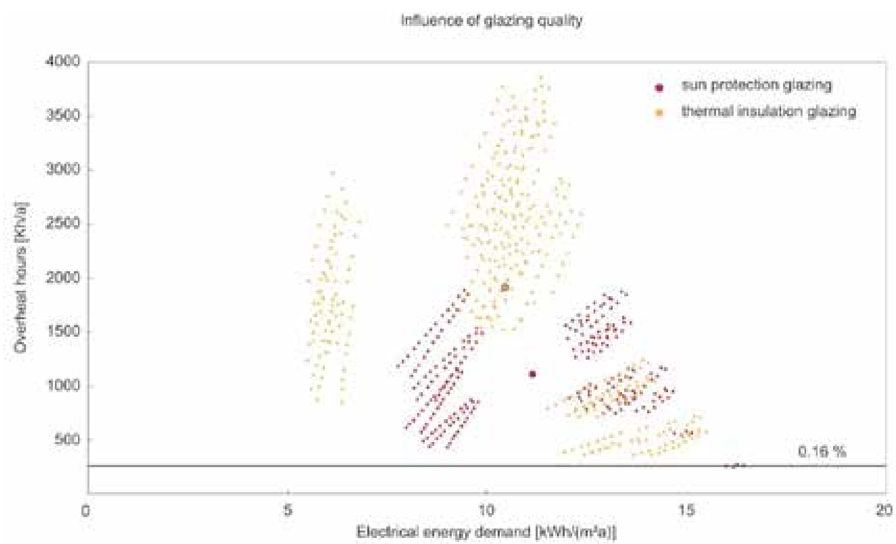

FIG. 4 Scenario 1: (heater + passive parameters): influence of glazing quality

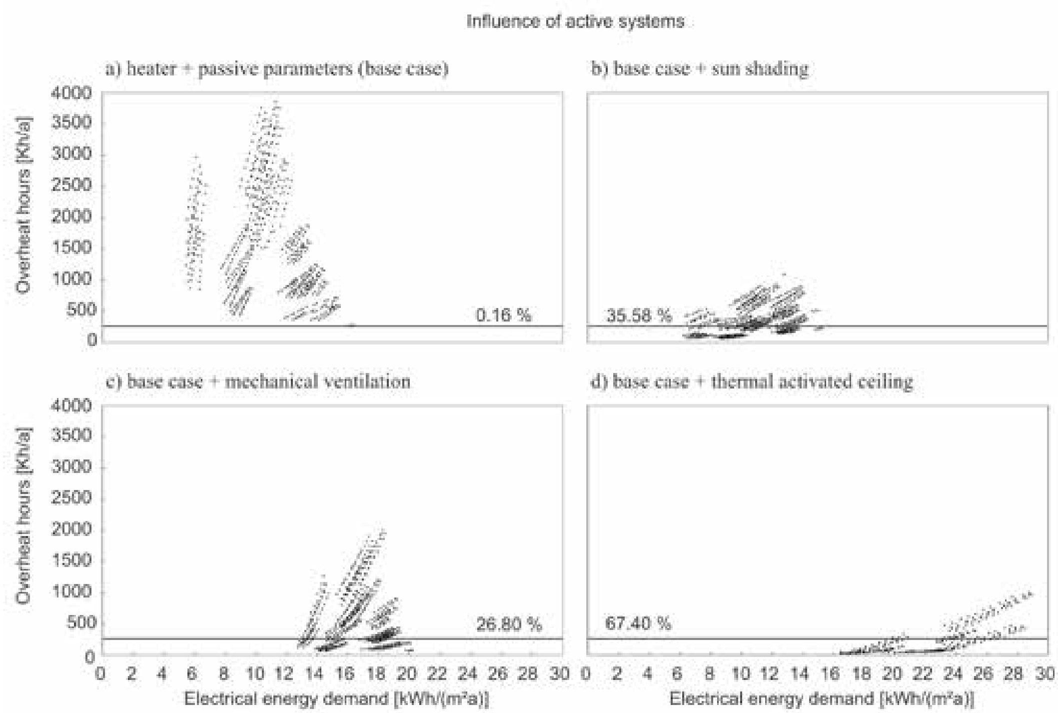

FIG. 5 Influence of active system implementation: a) base case, b) base case + sun shading, c) base case + mechanical ventilation, d) base case + activated cooling ceiling

In every point cloud graph, the x-axis shows the electrical energy demand in kWh/(m^2a), the y-axis shows the overheat hours in Kh/a. The main result is that the distribution of the point cloud only changes if an active system is added (Fig. 5). It is to note that one passive parameter even in the façade is always significant and determines the shape of the point cloud. This shows that orientation - regardless of the façade design - has the greatest influence on performance. The decision on the urban design and the main orientations of a building is therefore high significant for the further decicions.

As shown in the figures, the maximal passive strategy does not fit the comfort requirement of 261 Kh/a overheat hours according to DIN EN 15251, which is a standard European method for determine comfort threshold (DIN EN 15251, 2012). Only a few variants of north orientated configuration – comprising 0.16 % of the total variants – match the benchmark for overheat hours.

Fig. 5 gives a comparative overview of the active system scenarios and the base case. Therefore, the graphs are scaled down and axis labeling sizes are not adjusted to fit the new value ranges, but instead they have the same value ranges as in the graphs above. The results show that only using a heater in wintertime, the energy demand is the lowest compared to the results of scenarios b) and d).

Implementing just one of the 3 technical systems (controlled outside sun screen; mechanical ventilation; thermal activated ceiling), the performance during the cooling period is increased. The best performance results for indoor conditions regarding overheat hours per year are generated by the thermal active ceiling (67.40 %). This system uses the thermal mass of the construction and is able to minimise peak loads in an efficient way. Although the electrical energy demand has the highest value of the three systems, it is the most efficient combination.

The two conditioning systems are only implemented as add-on systems for cooling (activated ceiling) and heat recovery with low supply air temperatures (mechanical ventilation). The potential to replace the ideal heater is not considered in order to keep results comparable.

4.4 PARAMETER RANKING

The mathematical method of standard deviation was carried out on the results for summery indoor comfort (overheat hours) and heating demand (electrical operative energy) – shown in chapter 4.3 – to identify the leading parameters for the four scenarios.

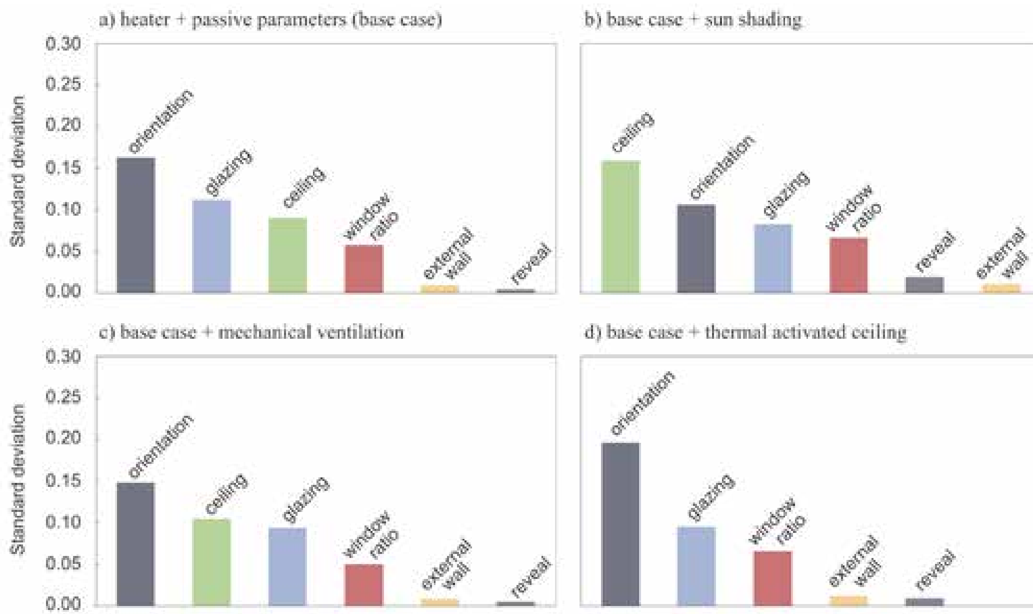

FIG. 6 Parameter ranking regarding overheat hours in summe

The parameter ranking for summer indoor comfort (Fig. 6) shows that the orientation has the highest impact on the indoor comfort, followed by the parameters glazing, respectively ceiling. However, implementing an outside sun shading system reduces the influence of the parameter orientation (scenario b)) and increases the impact of the thermal mass inside the building (ceiling). This concludes that the function of night cooling is decisive for the success of the system.

Using an active cooling system such as the thermal activated ceiling, the orientation is still the dominating factor. However, the influence of the physical characters of the façade (glazing and window ratio) is higher compared to the other ranked scenarios for overheat hours.

In terms of operative energy, the window ratio has the largest influence for nearly all scenarios, except the case of thermal activated ceiling, where the orientation is the leading factor.

All results show that there is nearly no influence of the self-shading effect by the depth of the wall. Based on this information we can argue that very thick wall construction has neither the impact on the winter performance nor the summer indoor comfort when compared to the parameter group of this study. This aspect only affects the environmental impact in terms of embodied energy.

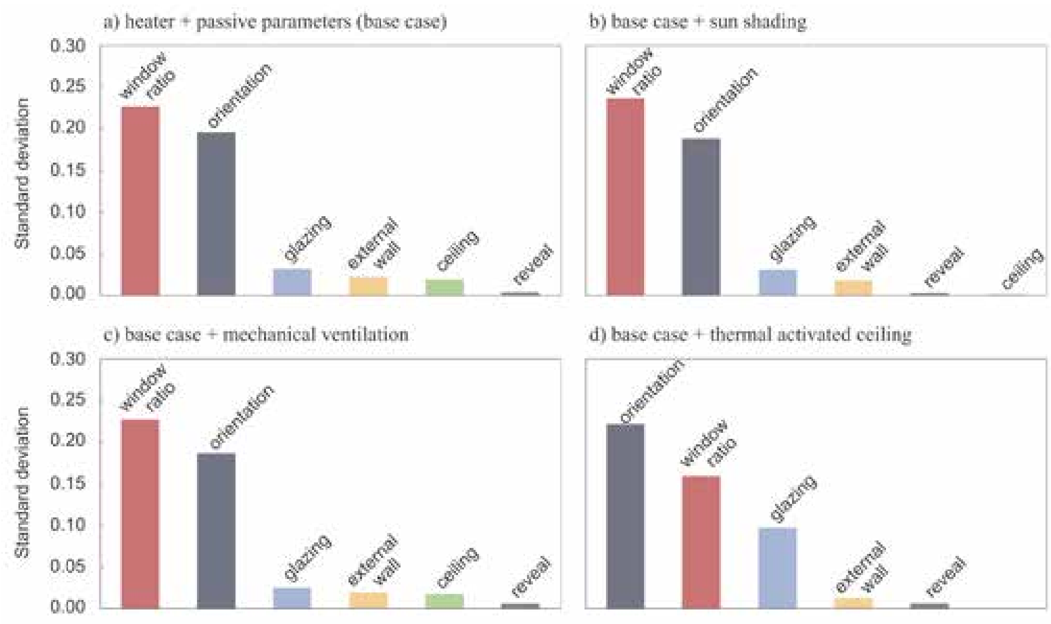

FIG. 7 Parameter ranking regarding operating energy demand

The total results show that implementing an active system leads to different parameter rankings. From the perspective of robustness, this means the lower the ranked parameter value the higher the robustness of the building's performance. Comparing the indoor comfort ranking (Fig.6) and absolute parameter values for energy demand (Fig. 7), one can observe that in sum the scenarios behave more robust regarding the summer indoor comfort compared to the energy performance in winter. It is to note that this is a comparative conclusion that cannot provide a total value for robustness.

5 CONCLUSIONS

Based on the results of the study at hand it can be concluded that Low-Tech in the context of robustness does not imply the full avoidance of technical supply systems nor to increase passive parameters to their maximum performance. Without any heating or mechanical ventilation system, indoor comfort according to standard cannot be provided during winter time within the study's boundary conditions. Likewise, indoor comfort is not met without any active system regarding the changing climate conditions, especially in summer. Reducing the window ratio as a passive optimization would increase the energy demand as well as cooling loads.

It is shown that the developed methodology provides comparative results on the robustness of building strategies. Further investigation is necessary to provide absolute values for robustness. However, this evaluation method can assist defining further parameters in the context of Low-Tech and robustness.

The answer to sustainable building strategies for the future will be an integrated design process. The goal of this process will be to reduce peak loads for heating and cooling in implementing passive parameters, and to create a high robustness toward unpredictable boundary conditions in reducing technical conditioning systems. In a next step the evaluation of the different technical systems, regarding the robustness of the system itself, would be helpful to complete the results and to give general advices for integrated Low-Tech strategies.

Acknowledgements
The authors' gratitude is due to the German government (BMI, BBSR), specifically the research platform Forschungsinitiative ZukunftBau, for supporting the project on hand. Likewise, the authors thank the German company POROTON GmbH for their support.

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3D Heat Transfer Analysis: A Parametric Tool for Designers

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Abstract
Due to the growing interest towards complex facade designs targeting highly optimised energy performance, 3D thermal simulations of building interfaces are today becoming increasingly important for designers. 3D heat transfer analysis, in fact, has the potential to assist designers during the earlier design phase to tune shapes, orientation and materials used in critical interface details, providing an important contribution to the optimisation of the building's energy performance and users' internal comfort.
Currently, a number of 3D heat transfer simulation software packages are primarily used as "reactive" tools to assess the compliance of already engineered solutions, rather than assisting engineers and architects during the design phases. A strong need is identified for alternative "exploratory" tools that implement the parametric component into 3D thermal simulation, with additional geometry modelling capabilities.
As a response, a parametric design tool has been developed based on a surface modelling system widely used across the design industry, combining the use of Grasshopper and Rhino 3D with a solid heat transfer FEM solver (Strand7). This paper outlines the tool's workflow structure, as well as presenting a verification and validation exercise to EN ISO 10211:2017, the European standard for heat flows and surface temperatures detailed calculations, which also contributed to the refinement of the methodology.
This study is aimed at building an appropriate level of confidence in the developed parametric methodology, especially conceived to aid building envelope designers, allowing them to perform effective parametric assessments of complex building envelope interfaces. The possibility to carry out in an efficient way 3D thermal transfer simulation iterations and sensitivity studies is likely to allow envelope designers steering the design development of the facade systems towards highly optimised and energy efficient solutions.

Keywords
Facade engineering, Building envelope design, Thermal analysis, 3D heat transfer, Thermal bridging, Energy modelling, Surface temperature, Temperature factor, Energy performance, Computational design, Rhino3D, Grasshopper, Strand7 API, Optimisation, Software interoperability, Validation, Verification, EN ISO 10211:2017, Optimization

1 INTRODUCTION

A tendency towards the use of computational design tools has been witnessed in the recent years particularly among building envelope designers. Thanks to these tools, architects and engineers are able today to take control of the design development of the building skin, promoting optimisation studies of different nature through the early design phases. It is also worth noticing how the high potential demonstrated by computational design studies is currently encouraging contemporary architecture trends to explore possibilities for increasingly complex shapes. Form finding, panel geometry rationalization, structural frame optimisation are amid some of the most widespread studies being carried out by facade designers when tackling complex problems. However, demanding energy performance requirements are also generating a strong need to implement building solar design optimisation studies alongside these others. Over the coming years, building skin design optimisation is expected to lean strongly towards energy loads minimization, providing a key contribution to the reduction of CO_2 emissions associated with the built environment. Alongside the above mentioned solar design optimisation studies, this identifies a need to establish computational design procedures for tackling detailed thermal performance analysis such as 3D heat transfer simulations. Although historically used predominantly by academic researchers or specialist facade contractors, detailed 3D heat transfer analysis is now considered to play a key role within the building envelope design discipline, which constantly pursues the optimum balance between visual appearance, minimalism of details and technical performance. This in fact provides the possibility for tuning materials and geometry of critical interfaces towards carbon emissions reduction, occupants' comfort improvement and achieving architectural aspiration.

The currently available commercial 3D heat transfer simulation tools offer a "reactive" approach to already engineered designs, which require thermal performance assessment to demonstrate their compliance with the specified requirements, providing limited possibilities for implementing a parametric "exploratory" approach. These in fact allow modelling a specific construction without allowing the flexibility of changing the design parameters in a quick and effective way, as often required during the early design phases. Additionally, from the review carried out, the modelling of the construction is typically limited to squared shapes, based on incremental extrusions of a number of 2D sections (curved or tapered 3D elements are typically not possible to model).

This creates the need for an alternative 3D heat transfer simulation approach that allows the designer to model complex geometry, while providing the required flexibility for implementing parametric variables. Consequently, a parametric approach to 3D heat transfer simulations has been developed by combining the use of a surface modelling system, a computational design tool and a solid heat transfer FEM solver. The proposed approach deviates from the typical 3D heat transfer modelling methodology, hence it has been necessary for it to be tested against validation benchmarks.

In addition to a detailed description of the tool's methodology and workflow, this paper reports results from the EN ISO 10211:2017 software validation exercises carried out following the proposed approach. Following this, potential future outcomes and benefits of this approach are outlined at the end of the paper.

2 METHODOLOGY

2.1 COMPUTATIONAL DESIGN IMPLEMENTATION

As discussed, the aim of this study is to develop a tool which would enable parametric 3D modelling of thermal finite element analysis. The development of such a tool from scratch would be a large undertaking, instead existing software is leveraged to tackle critical parts of the tool. The three essential components of the tool are 3D modelling, parametric enabled workflows and thermal finite element analysis. These three components are fulfilled by utilising the software packages of Rhino3D, Grasshopper and Strand7 respectively.

In order to provide the required level of modelling flexibility, the geometry generation step within the developed tool is based on the use of Rhino3D. Rhino3D is a NURBS-based CAD software package which is particularly capable at dealing with complex geometry and freeform surfaces. 3D geometry can be modelled via command-line interface or simple clickable command options and click and drag interface. Various typical CAD solid operations exist such as: box, sphere, cylinder, pipe, cone, extrude surface. Rhino also features some solid Boolean functionality (union difference, intersection) which aids the creation of 3D geometry for thermal analysis purposes.

Grasshopper is a plugin which is available for Rhino3D which provides an environment to model algorithmically and parametrically through the use of visual programming, as such no coding knowledge is required by the user. The software is already fully integrated with Rhino3D.

Rhino and Grasshopper also have a Software Development Toolkit (SDK) which allows for custom scripted components and plugins for Rhino and Grasshopper in order to expand the functionality of Rhino and Grasshopper to meet specific individual requirements. The SDK was applied for the development of the tool in this study.

Strand7 is chosen as the FEA thermal solver for this application. Strand7 is a general-purpose FEM software package which includes various solvers such as linear and non-linear static solvers, natural frequency solver, dynamic solvers and thermal solvers (both steady state and transient). The reasons that Strand7 has been chosen for this application are two-fold. Its API (application programming interface) capabilities allows interoperability of one software to another via custom scripting, in our case all coding is done in C#. Secondly, Strand7 has a powerful 3D automesher which will allow for automatic meshing of various geometries.

2.2 WORKFLOW OVERVIEW

Although Strand7 is used as the FEM solver, the tool which has been developed is opened and operated via a grasshopper script. A Strand7 file is created in the process of using the tool, this can be opened, inspected and further manipulated by the user but it is the intention of the tool that this is not necessary and all user interaction, including visualisation and extraction of results can be realized via the one interface.

The thermal analysis of a 3D detail begins with the 3D geometry. In implementing the tool, the user is able to either model the 3D geometry within the Rhino environment or if they prefer to define it parametrically within the Grasshopper environment, or a combination of both. Geometry modelled in Rhino can later be manually manipulated whereas Grasshopper defined geometry is more open to parametric manipulation.

The thermal FEM model parameters such as the boundary conditions (ambient temperatures and conduction coefficients) and material properties are defined within the Grasshopper environment through entering the relevant numeric data into Grasshopper panels. The boundary surfaces are selected from the existing 3D geometry using a bespoke tool that has been developed to easily allow user selection of the surfaces through mouse clicks on the relevant surfaces. Optional meshing parameter such as mesh density and local refinements are also available to the user. The ability to define mesh parameters however does lead to questions of the suitability of the mesh to accurately model the thermal behaviour of the particular detail. As such a sensitivity study has been undertaken in order to evaluate some rules of thumb as detailed in a later section of this paper.

After geometry and relevant parameters are defined, the user initiates the FE analysis via the Grasshopper interface, this part of the process involves a number of custom scripted components to deal with geometric cleaning, surface alignment, and ensuring mesh continuity followed by the FE analysis via Strand7 and visualisation of the output. After the analysis is complete and results have been collected by the Grasshopper script, the user is able to manipulate the result display, also via the Grasshopper interface. Further processing is also available to the user.

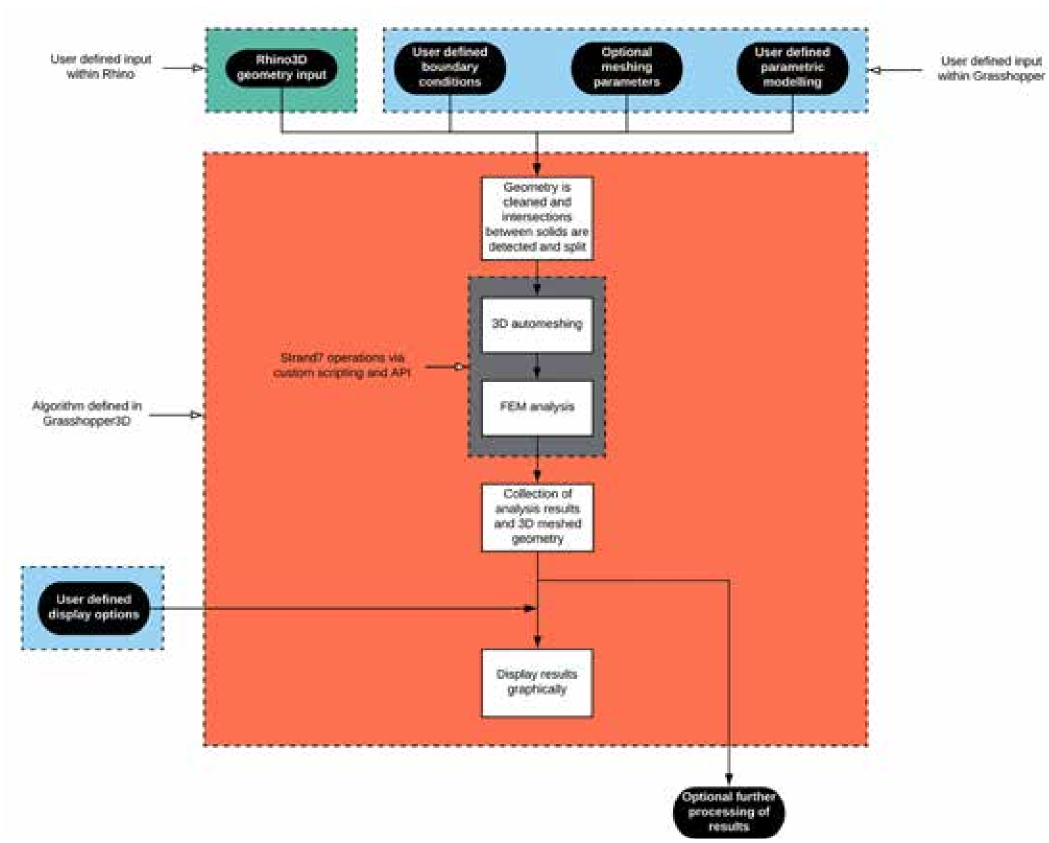

FIG. 1 Workflow of tool developed

2.3 INTEROPERABILITY

The final tool that has been developed requires no coding knowledge to use but relies heavily on custom scripted components in order to enable the two software packages to communicate with each other. The Strand7 API and Rhino SDK have been used to enable this interoperability. All coding has been written in C# and to allow for maximum flexibility in the future and for bespoke modifications of the script by users who are fluent in C# and the use of the Strand7 API we compile the script at runtime which means that the experienced user can, if needed, modify and augment the tool, however this was not part of the primary objective of the this paper. More minor modifications can be made in the Grasshopper script to suit the users needs, again this will not be necessary for the vast majority of cases but is an additional feature of the tool.

In order to increase the usability of the tool, the interoperability between Rhino/Grasshopper and Strand7 are bi-directional meaning that defining the model parameters, analysing the model and viewing the results can all be done from one interface, namely the Grasshopper script. As well as enabling results to be displayed visually, having the raw results of temperature and heat flux within the parametric environment of Grasshopper also allows analysis results to be further processed to calculate minimum temperatures, u-values, determine the locations of various points of interest, draw isotherms etc. as would be expected from many of the commercially available, dedicated thermal analysis software packages.

2.4 VERIFICATION AND VALIDATION

A model verification and validation exercise was undertaken as part of the tool development. These two crucial steps are generally considered to be part of the iterative process taking place throughout the model development phase (Sargent, 2011). Model verification is aimed at “ensuring that the computer program of the computerized model and its implementation are correct”, whereas model validation consists in a “substantiation that a computerized mod, within its domain of applicability, possesses a satisfactory range of accuracy consistent with the intended application of the model” (Schlesinger et al.,1979).

The verification and validation procedure provided an opportunity to test the tool under varying circumstances, this testing provided feedback on the usability of the tool, the generalisability of the tool, and provides a means of assessing the sensitivity of input parameters which are inherent in the tool implementation. Model validation also helped building a level of confidence in the results obtained as well as increasing the “credibility” of the tool among its users.

Among the available test methods, the comparative test procedure was identified as the most appropriate in these circumstances. Comparative testing involves the comparison of simulation results from one tool with itself or with another previously validated programme (CIBSE, 2015). More specifically, the tool validation tests were performed by comparing outcomes of the 4 test cases described in ISO 10211:2107 firstly with the results provided by the standard and secondly with the results of three other 3D simulation tools previously validated and currently available on the market (i.e. Heat3; Trisco; Strand7). This was aimed at providing a further overall accuracy confirmation for the developed tool.

The ISO Standard 10211:2017, the European the standard for heat flows and surface temperatures detailed calculations, provides a validation procedure for the calculation method and the reliability of its results. In the annex C.1 of the document, 4 n. test reference cases are provided with associated benchmark results. As described in the standard, only the calculation methods providing results within the ranges described by all the test reference cases can be considered as high precision 3D steady state heat flow calculations methods.

It shall be noted that Strand7 has been validated previously against ISO 10211 and as such it can be considered an accurate analysis package for 3D thermal modelling. However, it is considered prudent to validate the developed tool against the same standard in order to verify the interoperability procedure. Typical potential risks of interoperability include: mismatch of units, loss of geometric information during export and import, dimensional tolerance issues, loss of accuracy due to model positioning in space which lead to significant rounding errors, errors occurring from assumptions of the retention of and general bugs and errors in the implementation of the tool.

Of particular note are the meshing parameters. During validation of the tool the authors were able to establish common rules of thumb for the mesh density of the model and determine whether higher order elements where more suitable and computationally efficient for the purposes of thermal modelling.

Numerous minor amendments to the tool were made throughout the verification and validation procedure where the authors considered additional features to be of significant value. Most of these amendments concern the visualisation of results within the Rhino/Grasshopper environment allowing the user to cut sections of the 3D model, evaluate temperatures at specific points on the geometry, calculate flow rates, etc.

3 VALIDATION STUDY RESULTS

3.1 TEST CASE 1

Test Case 1 involved the simulation of a simple 2D problem, prescribing temperatures results to be achieved at specific points throughout the constructions. Although this consisted in a 2D problem, test Case1 was modelled in 3D by assigning a nominal thickness to the construction. Moreover, as described in the standard, the steady state solution for the temperature field does not depend on the material properties for this specific application, hence any arbitrary material properties can be used for this exercise. Results obtained by the tool simulation of test Case1 were all found to be within the acceptable range of accuracy provided by ISO 10211:2017, which states that the maximum temperature difference between the obtained results and the analytical solution shall be of 0.1 °C.

The comparative exercise carried with the other tools showed that the results obtained from all the tools are well below the maximum acceptable deviation of 0.1 °C. A slight result inconsistency can be highlighted especially for the top half of the analysed construction (points 1-14). This is believed to be due to the different calculation methods used within each tool, which provide slightly different results closer to the top left corner where the 20 °C boundary condition meets the 0 °C one. However, also for these points, the overall accuracy of the results obtained with the Tool was found to be aligned with the other software results.

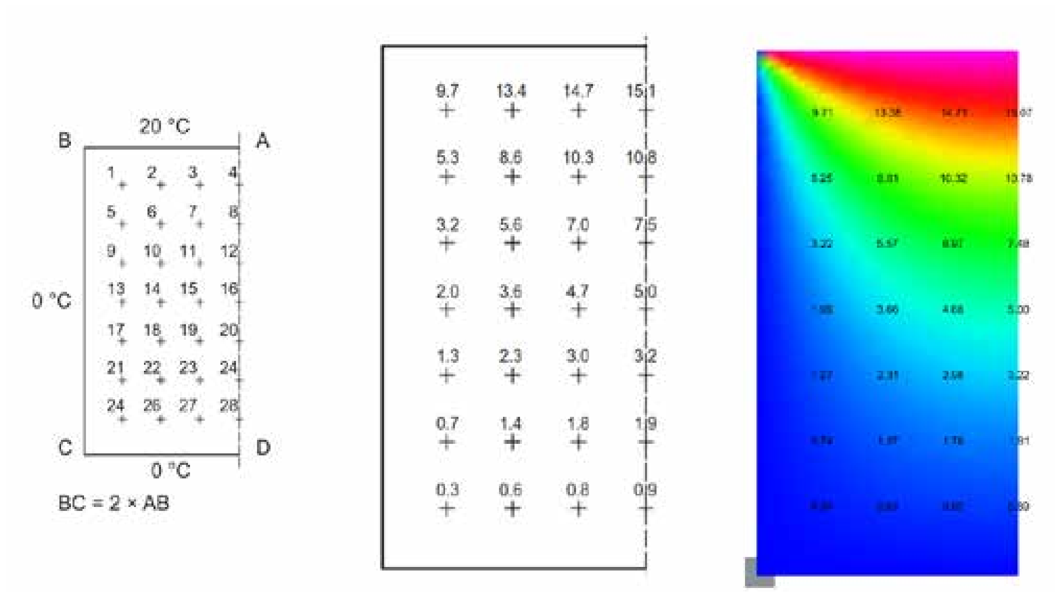

FIG. 2 left: *ISO 10211:2017 Case 1 input parameters, middle: ISO 10211:2017 analytical solution results, right: Case 1 simulation results*

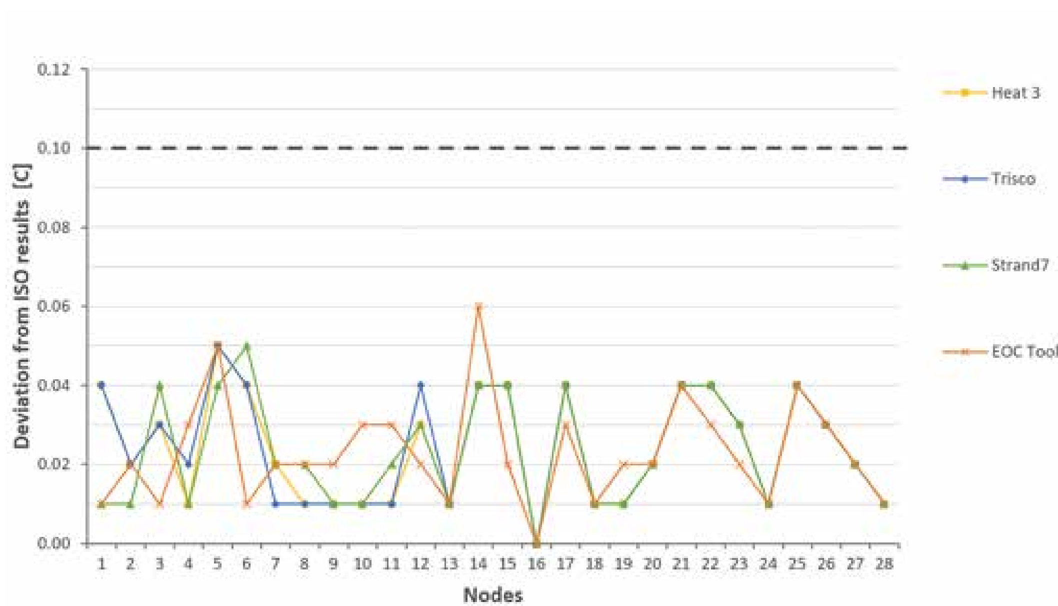

FIG. 3 Comparative study – Temperature result deviations from analytical solution

3.2 TEST CASE 2

In this test case exercise a vertical section of a building construction was modelled. Similarly to Case 1, this exercise was modelled in 3D by assigning a nominal thickness to the construction. For Case 2, the ISO standard identifies two criteria: an error tolerance of maximum 0.1 °C for the minimum surface temperatures, and a maximum error of 0.1 W/m for the calculated heat flow rate. Results provided by the tool for Case 2 were again found to be within the acceptable tolerance.

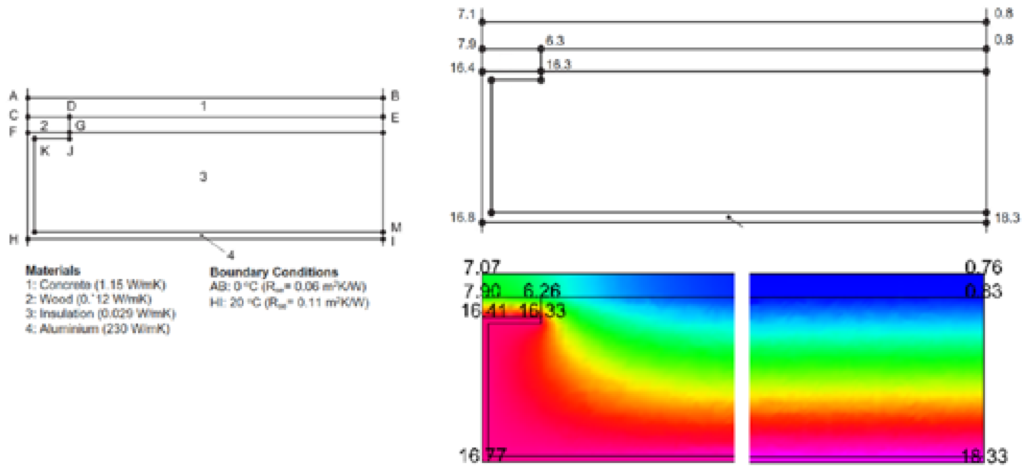

FIG. 4 left: *ISO 10211:2017 Case 2 input parameters, right: ISO 10211:2017 target results (A) and Case 2 simulation results (B)*

From the comparative exercise carried out between the tool and the commercial software, all temperature results deviations obtained appeared to be generally in line with each other. In is also worth noticing that the maximum observed deviation from the theoretical result was observed to be of 0.04 °C, well below the maximum threshold of 0.1 °C. This shows that the tool proposed, not only meets the requirements of the ISO standard for Case 2, but also features the same level of accuracy of the other software calculation methods assessed.

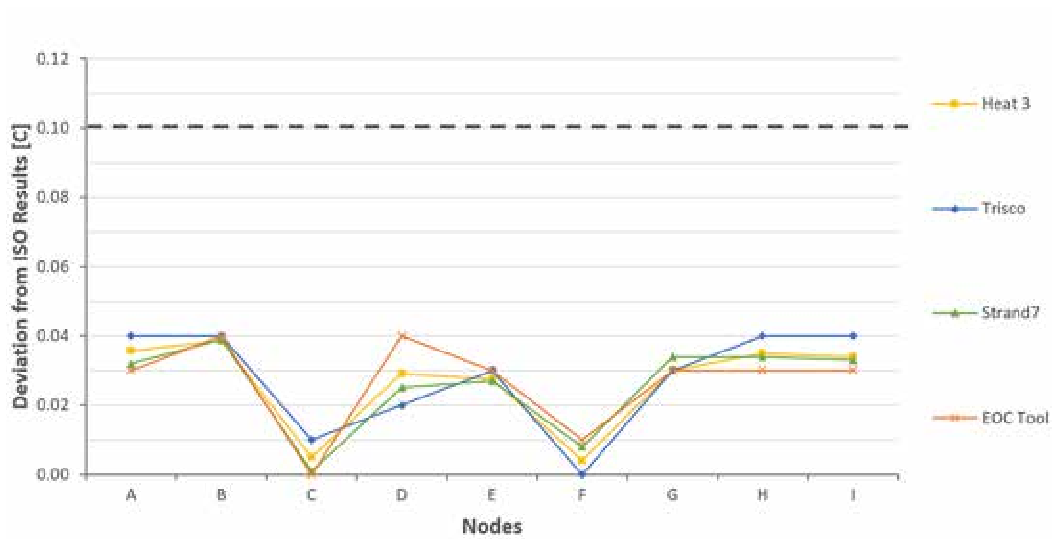

FIG. 5 Comparative study – Temperature result deviations from ISO target

3.3 TEST CASE 3

The steady state heat transfer problem described by ISO Case 3 involves the modelling of a 3D building corner with walls, floor and projecting slab. Within this test case, the standard identifies one criteria for surface temperature results (difference less than 0.1 °C) and another for heat flows between the different environments (shall not exceed a 1% difference with the target values).

For the heat flow results accuracy assessment, the following equation was used to evaluate the percentage difference:

$$\Delta\% = \left| \frac{\varphi 1 - \varphi 2}{\frac{1}{2}(\varphi 1 + \varphi 2)} \right| \qquad \text{[EQ 1]}$$

Where:

φ1 is the ISO 10211:2017 target heat flux value
φ2 is the heat flux result calculated

All Test Reference Case 3 results obtained by using the proposed calculation tool were found to be largely within the acceptable tolerances of the standard for both surface temperature and heat flow calculation tolerance criteria.

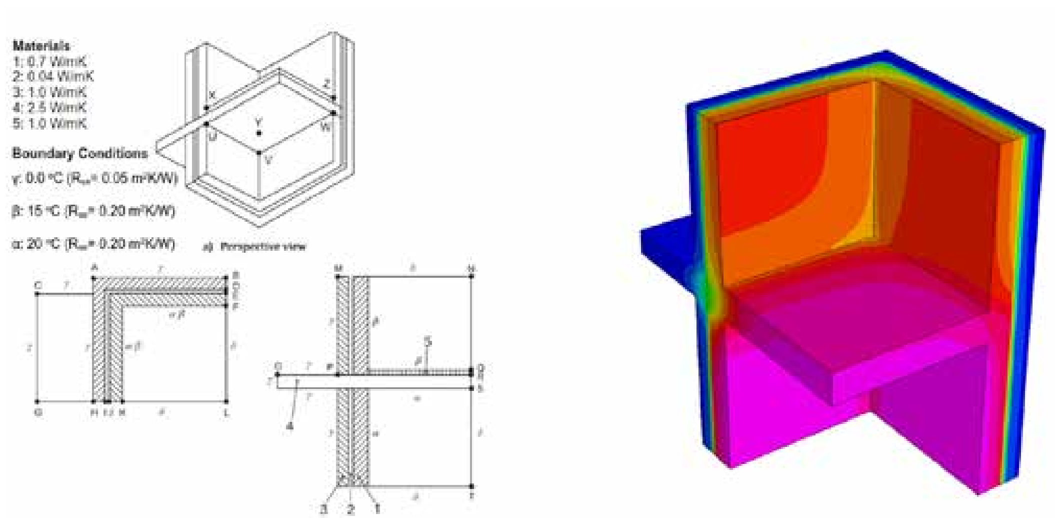

FIG. 6 left: ISO 10211:2017 Case 3 input parameters, right: Simulation model output temperature plot

The comparative exercise with the other software highlighted an overall consistent high results accuracy, with extremely low errors in both surface temperature and heat flow results.

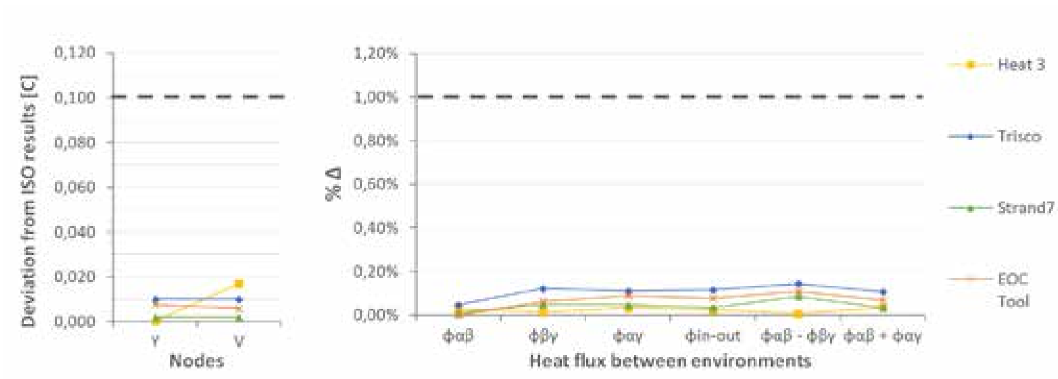

FIG. 7 Comparative study – Temperature and Heat flux result deviations from ISO target

NODES	10211:2007 CASE 3	EOC TOOL	
	Target T [C]	Calculated T [C]	ΔT < 0.1 °C
Y	11.110	11.102	0.008
V	11.320	11.314	0.006
Heat Flow between environments	Target φ1 [W]	Calculated φ2 [W]	Δ% < 1%
φαβ	10.470	10.47	0.00%
φβγ	24.360	24.38	0.06%
φαγ	35.620	35.65	0.09%
φin-out	59.980	60.03	0.08%
φαβ - φβγ	13.890	13.91	0.11%
φαβ + φαγ	46.090	46.12	0.07%

TABLE 1 ISO 10211:2017 Target results and Case 3 simulation results

3.4 TEST CASE 4

The fourth and last test case prescribed by ISO 10122:2017 involved a high precision 3D thermal simulation of an insulation slab element with solid iron beam penetration. In order to validate the precision of the tool, the boundary condition at the two sides of the construction differ only by 1 °C. This makes test reference Case4 the most rigorous to pass, as, due to the low temperature difference, the deviation tolerance provided by the standard becomes very stringent. In fact, the maximum allowable result deviation for the minimum surface temperature is set to 0.005°C, whereas, similarly to the other cases, the maximum percentage difference of the calculated heat flow though the construction is set at 1%. However, due to the very limited heat flow, the allowable heat flow result difference is also very strict. This requires a high precision of the tool subject to Case4 testing.

It shall be noted that this test case simulation required additional refinements of the proposed tool. During the iterations of simulation carried out for Case 4 a mesh size optimisation study was performed. In fact, an opportunity arose for improving the precision of the methodology proposed, as the same settings used for the previous test cases did not allow achieving acceptable results.

Thanks to the mesh refinement study, the results obtained were observed to be again in line with those of the assessed software.

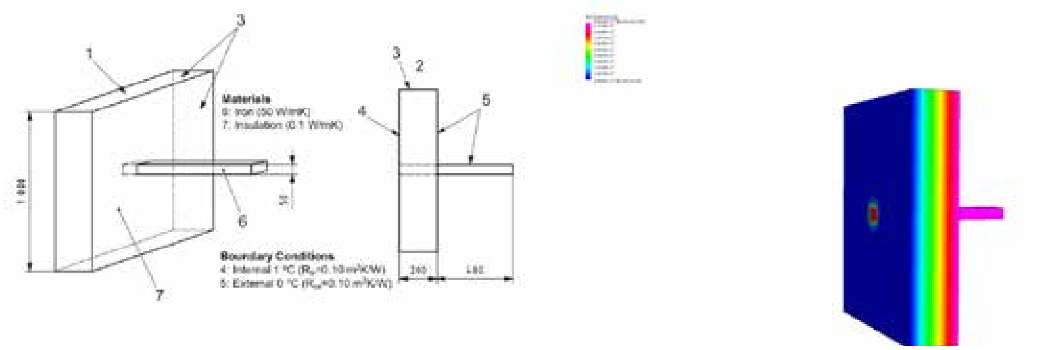

FIG. 8 left: ISO 10211:2017 Case 4 input parameters, right:Simulation model output temperature plot

	10211:2007	HEAT 3		TRISCO		STRAND7		EOC TOOL	
Max T	Target T [°C]	T [°C]	ΔT ≤ 0.005	T [°C]	ΔT ≤ 0.005	T [°C]	ΔT ≤ 0.005	T [°C]	ΔT ≤ 0.005
	0.805	0.805	0.000	0.800	0.005	0.800	0.005	0.801	0.004
Tot φ	φ1 [W]	φ2 [W]	Δ% < 1%	φ2 [W]	Δ% < 1%	φ2 [W]	Δ% < 1%	φ2 [W]	Δ% < 1%
	0.540	0.539	0.1%	0.54	0.0%	0.54	0.2%	0.542	0.4%

TABLE 2 ISO 10211:2017 Target results and Case 4 simulation results comparison

4 FURTHER DEVELOPMENT

At the moment the tool is separated by multiple steps within the Grasshopper script, the grasshopper script contains a number of native Grasshopper components and various custom scripted components. Moving forwards the authors would like to amalgamate these separate operations with the view to improve computation speeds; and reduce the complexity of the script, thus making it more user friendly.

General computation time improvements will also be something the authors will look to advance. Although the script is currently not slow, improvements with computation time will allow for more complicated models to be analysed and provide more opportunities for optimisation where multiple analyses are required.

Other improvements, which are considered for future development, concern collecting and presenting results. The authors wish to make it easier to visualise exactly what the user is concerned with along with creating automated ways of calculating U-values, localised heat losses and temperature factors from node temperature and heat flux data.

5 CONCLUSIONS

The workflow of the 3D heat transfer simulation tool developed was verified and its results were validated against ISO 10211:2017, hence, in its current state, this can be classified as a high precision simulation tool, similarly to other commercially available software.

The parametric nature of the tool developed is considered to be the most powerful feature that differentiates it from the current “reactive” 3D thermal analysis simulations. The possibility of modelling complex interfaces with a surface generating software (e.g. Rhino3D) and the flexibility offered to effectively tune key parameters without needing to re-model the 3D geometry at each iteration, are believed to be increasingly valuable to aid building envelope designers in the coming years.

Additionally, it is believed that the parametric environment offered by the proposed tool is likely to open a number of possibilities for implementing optimisation studies of different nature. This is also considered to provide the opportunity for extending the use of 3D heat transfer simulations to a collection of details forming part of a complex building skin, potentially informing design decision based on energy performance alongside those based on structural behaviour and solar control.

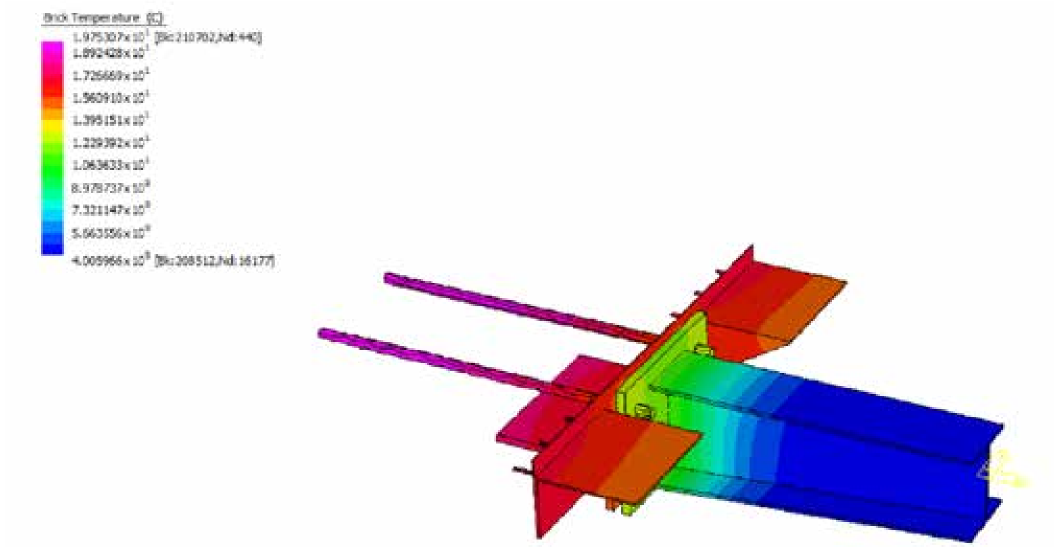

FIG. 9 Example of the geometric complexity which can be accommodated by the developed tool

Acknowledgements

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A Study on the Impact of Climate Adaptive Building Shells on Indoor Comfort

Abstract Only! Full Paper in JFDE 2019.1

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Abstract

Energy savings and indoor comfort are widely considered to be key priorities in the current architectural design trends. Additionally, the well-being and satisfaction of end users is a relevant issue when a human-centred perspective is adopted. The application of Climate Adaptive Building Shells (CABS) compared to conventional façades offers appropriate opportunities for tackling these challenges. This paper reports the outcomes of a study performed on CABS in order to optimise the indoor comfort while calibrating the configuration of a dynamic façade module. The horizontal louvres of the adaptive façade are moved by an actuator that exploits the expansion of a thermo-active resin as it melts, by its absorption of energy. The actuation mechanism depends on the outdoor air temperature conditions and does not require a supply of energy. The performed simulation evidenced a decrease of approximately 4°C indoors when the dynamic module is fully efficient (21st June at 12 p.m.). Furthermore, the lux level is always within the comfort range for an office building (500-2000 lux) during both winter and summer scenarios. The optimised solution shows a substantial gain for energy performance and environmental sustainability. Moreover, the uniformity of distribution of daylight illuminance across the entire space is another associated advantage, giving interesting insights into potentials for architectural façade design.

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Trombe Curtain Wall Façade

Abstract Only! Full Paper in JFDE 2019.1

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Abstract
In times of energy use awareness, decarbonisation, and resource efficiency, the performance of well-known façade components must be pushed beyond current limits through innovative designs and new combinations in construction. This paper presents an unconventional redesign of a double skin façade (DSF), based on Trombe wall principles, to enlarge solar gains in heating seasons and avoid overheating issues in summertime. The DSF variant is equipped with a thermal storage mass in the DSF cavity and interior insulation. The thermal mass, in this case concrete, is of a dark colour for high solar absorption, whereas the shading device is highly reflective. In contrast to traditional Trombe wall systems, this TCW is not supposed to actively heat interior space or transfer thermal energy. Instead, the TCW aims to regulate heat flux within the façade level by the management of solar thermal energy fluxes. The potential to reduce buildings' heat losses through solar energy use is shown and compared to a traditional external thermal insulation composite system (ETICS) with an appropriate insulation thickness for renovation purposes in Switzerland. The U-Value is therefore considerably lower, 0.25 instead of 0.41 for the TCW. Due to the innovative design and fully transient operation, a highly detailed and flexible simulation tool is needed to analyse and assess the façade performance. The decision to simulate the novel system was made for Modelica-Dymola, with its object-oriented, equation-based simulation language. The simulations of both TCW and ETICS show potential for heat loss reduction due to solar energy storage on every orientation. However, the TCW shows a high solar energy usage due to its 'natural' overheating tendency. Furthermore, heat losses are significantly lower than the U-Value predicts and, in some cases, even lower than the ETICS heat losses. In addition, due to its lower use of material and lower weight, the system can be used as a curtain wall system instead of traditional DSFs, which have higher heat losses in winter and higher solar gains in summer.

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