Active, Passive and Cyber-Physical Adaptive Façade Strategies: a Comparative Analysis Through Case Studies

Jens Böke*[1], Paul-Rouven Denz[1], Natchai Suwannapruk[1], Puttakhun Vongsingha[1]

* Corresponding author, Jens.Boeke@priedemann.net
1 Priedemann Fassadenberatung GmbH, Germany

Abstract
In view of the required energy savings in the building sector, there is an urgent need for innovative and sustainable solutions to increase the performance of building envelopes. Adaptive façades can make an important contribution, whereby passive low-tech strategies and active high-tech solutions are apparently incompatible. In current digitalization, new technologies and methods for the implementation of adaptive façades emerge in the framework of Cyber-Physical Systems. The investigation follows the research question: How can active and passive approaches of adaptive façades be mediated and what potential do Cyber-Physical Systems have for the implementation of hybrid solution approaches in the future? The article presents a comparative case study of the two research projects ADAPTEX and PRÄKLIMA as examples of passive and active adaptation strategies in the façade industry. In this context, the potential for further research of Cyber-Physical Systems in the application domain of adaptive façades as a catalyst for high-performance and multifunctional solutions, and as a mediator between both strategies, is highlighted. The main findings are the potential application of cyber-physical system technologies to the design and monitoring of passive adaptive façade solutions, as well as the possible integration of passively conceptualized components into active overall systems.

Keywords
adaptive façade, smart material, intrinsic adaptation, extrinsic control, artificial intelligence, prototyping, monitoring, ADAPTEX, PRÄKLIMA

DOI
http://doi.org/10.47982/jfde.2022.powerskin.01

1 INTRODUCTION

As part of the digital transformation of our society and economy, a wide range of new automation technologies emerges with associated strategies for their application (Gupta & Bose, 2019; Nambisan et al., 2019). Example disciplines are autonomous driving or the decentrally organized "smart factories" of Industry 4.0 (Pisching et al., 2016). The combination of mature cloud infrastructure and growing Artificial Intelligence (AI) capabilities is leading to a new generation of digital tools and methods that are showing their potential in many application fields through the deployment of Cyber-Physical Systems (Rajkumar et al., 2010). They promise greater efficiencies and more flexibility for architects, engineers, and developers. There is an ongoing debate as to whether they also contribute to a more sustainable built environment or promote "business as usual".

In view of ongoing climate change with global effects on our environment, the United Nations formulated the increasing need for action with regard to sustainable development in their goal definitions (United Nations Department of Economic and Social Affairs, 2021). In the European Union, the building sector accounts for about 40 % of primary energy consumption and 36 % of greenhouse emissions (In Focus: Energy Efficiency in Buildings, 2020). In line with global ambitions as formulated by IEA (2021) to become climate neutral by 2050, European measures include revising current policies by amending the Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (EED), which focus on nearly net-zero buildings, energy performance certificates, long term renovation strategies for EU countries, also taking smart and innovative technologies for new buildings into account (EUR-Lex - 52020DC0098 - EN, 2020).

In line with the formulated energy-saving targets, sustainability is a key issue in the construction industry and is pursued by various building strategies, like improved insulation of the buildings, building-integrated energy generation, and application of reversible construction methods.
In addition, smart technologies are discovered as a possible contributor to improved sustainability in the building sector. The existing building stock accounts for a large share of the energy demand, with approximately 75 % of the total building stock being energy inefficient. (EUR-Lex - 52020DC0098 - EN, 2020)

With the building envelope acting as a barrier between the indoor and outdoor environment it plays a crucial role in regulating the indoor environment which directly affects the energy performance of a building. Therefore, the design of an energy-efficient façade presents itself as one of the potential solutions to tackle the imminent issue as various researches have shown that adaptive façades have the potential to reduce the energy consumption of a building by up to 29 % (Bui et al., 2020; Shi & Pouramini, 2022). In addition to its role as a barrier between the indoor and outdoor environment, a high-performance sustainable façade should also serve as a building system that actively responds to the ambient environment and contributes to reducing the building energy consumption while providing optimal comfort to the users. (Aksamija, 2013)

2 ADAPTIVE FAÇADE STRATEGIES

In its role, as defined by Herzog et al. (2004), of an interface between the external climatic conditions and the desired indoor environmental quality of a building, the façade significantly affects the energy performance of a building, as well as the provided interior comfort. Adaptive façade systems offer considerable potential for optimization in this context, as they are able to adapt independently and dynamically to changing circumstances and requirements in order to provide the most efficient configuration of the construction for the respective boundary conditions (Kasinalis et al., 2014). In practice and according to the current state of the art, adaptive façades are mainly project-dependent, with only selective individual adaptive features like sun shading or ventilation. The overarching objective of holistic multifunctional adaptive building envelopes remains uncommon as commercially available products (Böke et al., 2019; Loonen et al., 2013).

There are two basic approaches to establishing adaptability: First, via a low-tech approach that makes use of physical effects and material behaviour. Loonen et al. (2013) classify this passive strategy as intrinsic adaptation due to its integrated actuation feature and the autonomy of its control. The second approach, as a high-tech solution, relies on the extensive use of automation technologies and digital control. Following Loonen et al. (2013), such systems can, due to the required external impulse to trigger adaptations, be accordingly defined as extrinsic.

2.1 PASSIVE ADAPTATION STRATEGIES

To tackle the immediate challenges of reducing carbon emissions and stalling global warming, it is generally acknowledged that passive strategies should be implemented as the first strategy in designing an energy-efficient building (Prieto et al., 2018). Due to their simplicity and low-threshold approach, passive strategies have been commonly practiced in vernacular architecture, designed to accommodate the immediate environment. Prominent examples of passive solutions include the use of wind towers for passive air conditioning in hot and dry climates and the use of trombe walls as a passive solar heating strategy in temperate climates (Maleki, 2011; Wang et al., 2021). Nevertheless, due to the changes in lifestyle, technological advancement, and higher requirements for high-performance buildings, passive features are also adapting to conform to architectural trends and modern lifestyles (Konis & Selkowitz, 2017). This is reflected in the recent façade developments which are multifunctional and highly adaptive systems, allowing the façade to change its functions to adapt to the immediate environment (Loonen et al., 2015).

In today's implementation of passive adaptation strategies, the application of smart materials plays an important role, as they enable the initiation of self-sufficient adaptation processes via material-immanent capabilities. Commercially introduced in the early 20th century, smart materials such as Nitinol are gaining acceptance as an alternative solution to meet the technological demands of today. Defined by Addington et al. (2007) as "highly engineered materials that respond intelligently to their environment", smart materials broaden the design possibilities and introduce new design options in various sectors including the building industry. In recent years there has been increasing investigation into how "smart materials" respond to various environmental stimuli. Hensel (2013) defines materials with such capacities as "material systems" based on their respective ability to react to their environment. In a similar understanding, Menges et al. (2014) explore the exploitation of intrinsic material properties to perform adaptations through the application of digital design methods. One example is the "HYGROSKIN – METEOROSENSITIVE PAVILION" project, in which wood composites allow for opening and closing the structure purely in response to changes in humidity (Menges & Reichert, 2015).

Due to the intrinsic characteristics, different research projects offer an alternative approach in place of mechanical shading and ventilation systems. Examples are the vertically moving screen system developed by Decker & Zarzycki (2014), an operable modular shading panel that incorporates two sets of counteracting SMA by Payne & Johnson (2013), and the project "Bloom", incorporating a thermal bi-metal shell structure which curls when heated to ventilate a specific area under the shell (Fox, 2016). The innovative solutions allow immediate response to the environment while presenting the potential to minimize energy consumption during operation. Nevertheless, despite operational simplicity and intrinsic characteristic, the automatic response to the environment can also create dissatisfaction for the users, as it limits personal control and often fails to accommodate the demands of different users, especially in a shared space (Luna-Navarro et al., 2020).

2.2 ACTIVE ADAPTATION STRATEGIES

Adaptive façades are today mainly implemented as part of building automation systems (BAS) on the basis of automation technologies (Böke et al., 2020a). Their operation is based on a set of electrical and mechanical devices that perform automated tasks assigned through a control network. According to the current state of the art, BAS are structured as hierarchically organized control concepts following the idea of automation pyramids as shown in FIG 1. (Cerf, 2010; Soucek & Loy, 2007). In a simplified understanding, they consist of a bottom assembly level with sensors and actuators of the system architecture, the digital direct controllers (DDC) and terminal strips for control and regulation in the middle levels, and the central control management at the top (Merz et al., 2009). Different product standards and platforms exist, such as ZigBee, KNX, BACnet, Modbus and LonWorks. Building automation systems themselves represent a potential solution to reduce energy consumption by controlling the HVAC system during building operation, enabling monitoring and maintenance, and thereby also providing user comfort. The development of building automation technologies is vendor-driven, which in practice often leads to integration problems due to inconsistent product standards and protocols (Domingues et al., 2016).

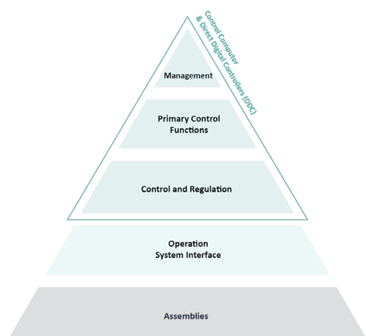

FIG. 1 Concept of the automation pyramid adopted from (Merz et al., 2009)

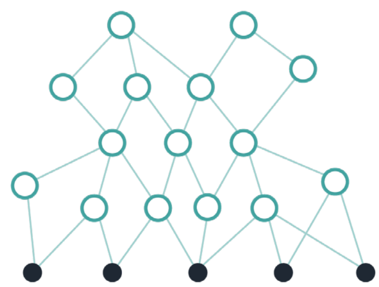

FIG. 2 Decentralized nature of Cyber-Physical Systems adopted from (Monostori et al., 2016)

According to the findings of Loonen et al. (2015), the main characteristic of active façade controls is the incorporation of feedback loops which allow for the current configuration or action to be evaluated by the desired state or a benchmark. Despite the wide range of operational characteristics and categorization of adaptive façades, active operations are based on three main stages: data collection or input, processing of the acquired data and finally executing physical actions as the output. Accordingly, automated adaptive façades comprise of a sensor system that collects relevant information as input data, a processing system that translates them into control parameters that are received by the actuators, and actuators that execute the control decisions as adaptation measures of the façade configuration.

One of the most common applications of active façade adaptations is dynamic shading devices. The dynamic aspect of the façade grants a higher level of design freedom for the designer to plan with a higher level of transparency without compromising to the limitation in thermal performances and window-to-wall ratio aspects. Therefore, they are usually implemented as machinal louvres, shutters, screens, or blinds, as a means to control solar gains and utilize passive solar energy (Loonen et al., 2015). These examples are evident in projects such as Q1 Thyssen Krupp Headquarter by JSWD architects, the Oval Offices by Sauerbruch Hutton, or a more sophisticated application at the Al Bahr tower by Aedas architects. In recent years, chromogenic façades gained increased attention and are becoming more commercially available. Due to its operational approach which relies on electrochemical reactions in the layers of semiconducting materials, mechanical parts are eliminated, and the system can run with low operating costs (Sandak et al., 2019). Active ventilation systems represent another example for extrinsic implementations of adaptive façades. They are usually integrated as automated operating windows to regulate natural ventilation or within closed cavity façades to control airflow and provide heat dissipation (Attia et al., 2020).

Automated adaptive façades occur as in the given examples with selective implemented automated functions and their integration into the BAS, while limitations still exist in the availability of holistically coordinated multifunctional adaptive façades. At this point, Cyber-Physical Systems, as explained in Section 1.3, can make a major contribution by allowing for highly flexible and decentralized control concepts.

Actively automated and controlled systems offer a high degree of flexibility and intervention possibilities in digital control. At the same time, they also entail a number of disadvantages due to the fact that they are high-tech solutions with a limited lifetime of the electrotechnical components and their susceptibility to malfunctions. This can lead to a high maintenance effort in the operation of actively automated façades. In addition, while offering the possibility of reducing the building's overall energy consumption by offsetting HVAC expenses, they are also primarily dependent on the additionally invested electrical power supply (Loonen et al., 2013).

2.3 CYBER-PHYSICAL FAÇADE SYSTEMS (CPFS)

Cyber-Physical Systems (CPS) are the main driver of the current digital transformation of our society and environment. They are based on the close interaction of physical products, plants, and systems with their digital control (Broy, 2010). The technical requirement for this integration is the possible embedding of physical devices with independent processing capabilities, which is possible today due to both miniaturization and the increase in the performance of computer technologies (Wolf, 2012). An important aspect of CPS is its shift from the former hierarchical automation pyramid organization (FIG 1) to cloud-based networking and decentralized control as shown in FIG 2 (Monostori, 2014).

In addition to their appearance in the form of the Internet of Things (IoT), Cyber-Physical Systems find their application in many different sectors today, such as medicine, transportation, power grids, and industrial production (Jamaludin & Rohani, 2018). In building industry, Cyber-Physical Systems are already being researched and deployed, as described by Bonci et al. (2019) for building efficiency monitoring, in fabrication and computer-aided manufacturing processes as presented by Menges (2015), and smart building automation (Karbasi & Farhadi, 2021; Reena et al., 2015). A prominent application field is smart factories of Industry 4.0, where such systems are defined as intelligent technical systems (Dumitrescu et al., 2013). Their implementation is closely related to the development of digital twins (Biesinger et al., 2019; Negri et al., 2017). According to the basic concept of CPS, individual plants of production lines are equipped with individual control and networked to form decentrally organized production systems (Herwan et al., 2018). The aim is to increase both the productivity and flexibility of the production processes (Monostori, 2014). The utilization of the Cyber-Physical System concept is evident in various industrial sectors ranging from equipment manufacturers, and operators, as well as service organizations such as airport facility management (Herterich et al., 2015).

Under the similar objective of increasing flexibility and energy performance, Cyber-Physical Systems can also be applied to automated adaptive building envelopes. The corresponding implementation of a cyber-physical façade system (CPFS) was investigated by Authors in the development of a prototype which, in addition to its physical components with deployed sensors, actuators, embedded control, and realized communication system, also includes a representation as a digital twin for monitoring the system behaviour. Automated individual façade functions such as solar shading, ventilation, and heating and cooling were part of the consideration. Based on the environmental information provided by the integrated sensors, the instances of the automated façade functions make independent adaptation decisions via feedback loops on the installed microcontrollers and coordinate these via the communication system to coordinate measures of the overall system (Böke et al., 2020b). The result is a flexible and independently operating organism of individually automated and cooperating façade functions.

In comparison to other industrial sectors, the innovative automation strategy of Cyber-Physical Systems had just been introduced in the Architectural, Engineering, and Construction (AEC) fields, therefore, their application is still premature (Böke et al., 2019). Many open questions remain regarding relevant façade construction and automation technologies, advanced control concepts, and current implementation strategies. This can be further specified to the following core topics still to be investigated: In addition to the structural implementation of cyber-physical façades, one main aspect is to increase the efficiency of decision-making processes at the higher control level by using AI strategies. Another open question is on the provision of project-specific tailored datasets, which requires both the selection and component integration of appropriate sensor technology. From an accessibility point of view, the interaction between users and the façade is an interesting aspect that has not yet been thoroughly explored in the field of CPFS. In this context, similar to the inability to obtain full control over the system, relates to passive solutions described in section 1.2.1, the effects of adaptation processes on user comfort as well as the user's possibilities to interact with the cyber-physically automated façade are relevant open questions. Nevertheless, in view of the technological capabilities existing today, the research on CPFS already shows great potential for automated system application, especially in adaptive façades. This is due to the integrated nature of physical construction and its embedded digital control, which enables further digital optimization strategies like the application of AI and machine learning. AI is increasingly recognized for use in architecture and façade engineering (Chaillou, 2022; Kraus & Drass, 2020). In this sense, cyber-physical façades represent a door opener, especially for performance-enhancing innovations on the cyber level.

3 PROBLEM STATEMENT

While the adaptability of façades has been already recognized and intensively researched as a strategy for improving the energy performance of buildings, solutions to date are mostly fragmented and project-dependent implementations of individual adaptive functions (Aelenei et al., 2016; Loonen et al., 2013). The goal of holistically conceived implementations of multifunctional and well-coordinated overall systems remains largely unachieved in the implementation of adaptive façades to date. In particular, a disconnect exists in the two contrasting mindsets of either a passive low-tech solution, for example via the use of material-inherent smart properties formulated by Hensel (2013), and an alternative high-tech approach via extensively equipped automation technologies and digital control.

4 OBJECTIVE

In response to the posted problem statement, the objective of this paper is to review previous theories behind active, passive and cyber-physical systems and compare these concepts in a physical case study. It therefore elaborates the ongoing investigation of two exemplary Research and Development projects, ADAPTEX and PRÄKLIMA, which represent the described passive and active approach to adaptivity and already implemented aspects of Cyber-Physical Façade Systems (CPFS) in their design framework. Insights from the research by design process and the utilization of the Cyber-Physical system framework is described to establish a base for discussion in examining the possibility of a hybrid adaptive façade system.

One goal of the study is to question both ways of thinking and to explore possible interfaces. Cyber-Physical Systems represent a new stage of development in automation in many fields of application (Rajkumar et al., 2010). In this context, it questions how correspondingly available technologies and application methods can play a mediating role and contribute to future comprehensively adaptable façade systems. Accordingly, the paper follows the research question: How can active and passive approaches of adaptive façades be mediated and what potential do Cyber-Physical Systems have for the implementation of hybrid solution approaches in the future?

5 CASE STUDIES: ADAPTEX AND PRÄKLIMA

5.1 METHODOLOGY

The study discloses the experiences from the prototypical implementation of both projects and draws a comparative balance of the two solution approaches between passive implemented adaptivity and active control. Two research projects, ADAPTEX and PRÄKLIMA, demonstrate the application of smart materials, digital technologies, and respective methods in order to reach desired façade performance objectives. Therefore, they have been selected as case studies to examine the implementation of the Cyber-Physical system through its roles as either a facilitator or a mediator, in a passive or active implementation potential of adaptative measures in the building envelope. In both cases, the test operation on the 1:1 scale prototype and the related assessment of the actual contribution of the respective concept to the energy performance of the façade are presented and discussed.

ADAPTEX is an autarkic and adaptive textile sun shading solution which implemented the smart material, Shape Memory Alloy (SMA) as an actuator. The system operations and the employment of the Cyber-Physical system framework as a facilitator through the series of sensors system which enables an effective selection of 'smart materials' that is tailored to a site-specific context and monitoring the behaviour of the passive operation of the system is discussed in the result section.

On the other hand, PRÄKLIMA is a self-sufficient modular, unitized façade system which incorporates an air-conditioning system and solar control with a predictive, self-learning control system. It represents an active system that enables automated and multi-functional adaptations. Hence, the role of Cyber-Physical system as a mediator between design variables to enhance the decision-making process of a machine learning integrated decentralized façade system will be examined.

The potential of both approaches is reflected with regard to further investigation from the viewpoint of a cyber-physical realization of a hybrid façade system as illustrated in the methodology diagram in FIG 3. Furthermore, an outlook toward a more comprehensive implementation of CPFS in the building industry is presented in the Discussion chapter.

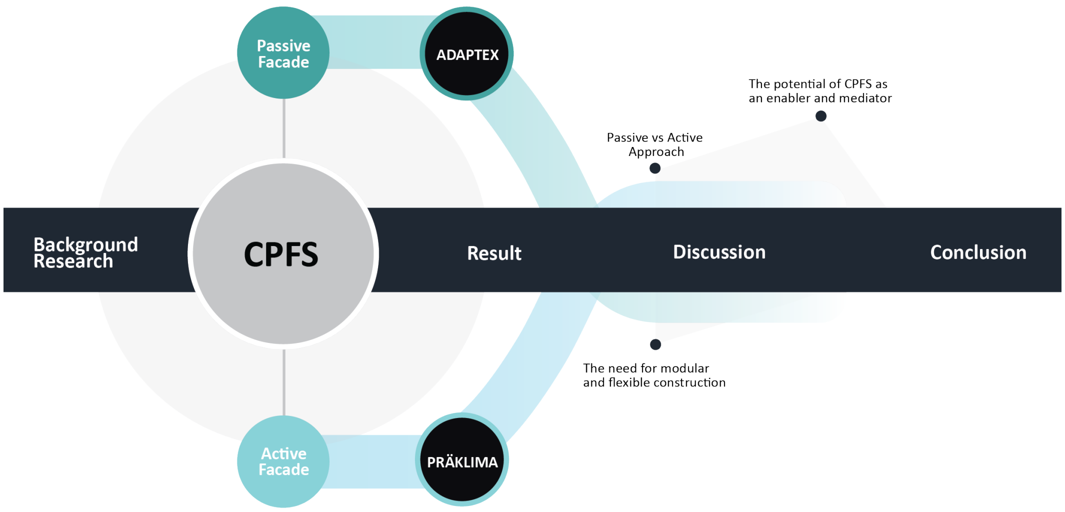

FIG. 3 Methodology diagram

The following two sections document the implementation of the research projects ADAPTEX, an autarkic and adaptive textile sun shading solution, as an exemplary application of a passive adaptation strategy, and PRÄKLIMA, a self-sufficient modular, unitized façade system which incorporates an air-conditioning system and solar control with a predictive, self-learning control system, in terms of an automated and active control of adaptation measures.

5.2 RESEARCH PROJECT ADAPTEX AS PASSIVE APPROACH TO ADAPTIVITY

The ADAPTEX research project focuses on the investigation and development of integrating Shape Memory Alloy (SMA) as an actuator in textile, adaptive sun shading solutions to achieve an autarkic operation that passively adapts themselves to the changes in ambient temperature. (Denz et al., 2021) Shape memory alloys (SMA) are among the so-called smart materials. They react to temperature changes through deformation and/or shrinkage, depending on their geometry and the predefinition of their material configuration. The ADAPTEX project takes advantage of this effect by integrating SMAs as wires into the textile structure and using them as actuators inducing high forces relative to its size to operate the system.

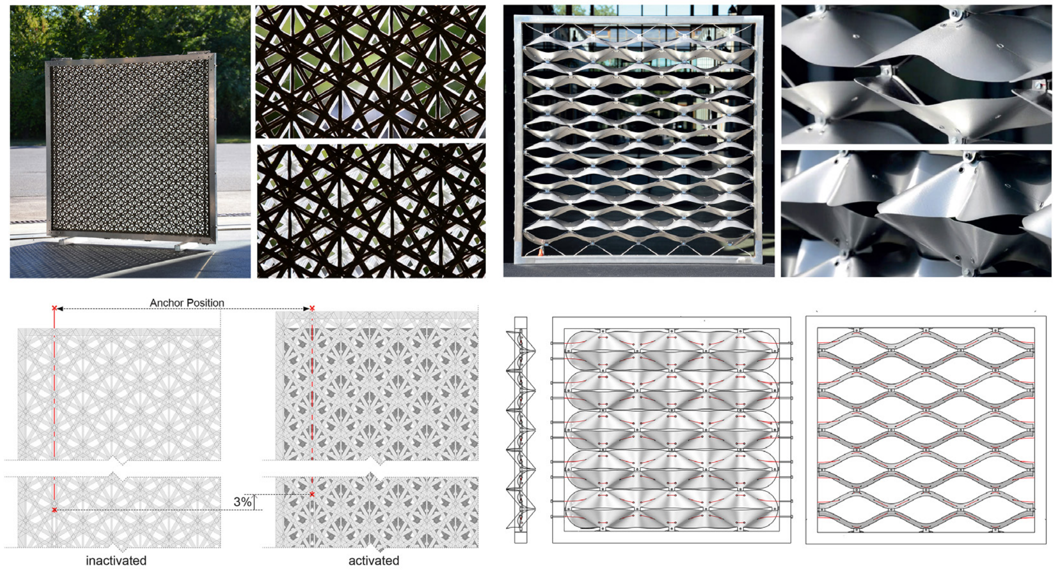

FIG. 4 ADAPTEX textile adaptive sun shading concepts: Mesh on the left - Wave on the right.

Two concepts have been developed following the principle of the SMA behaviour. The concepts, ADAPTEX Mesh and ADAPTEX Wave differ both in their textile structure and kinetic mechanism. ADAPTEX Mesh consists of two identical non-woven textile layers. The operation relies on the SMA which is integrated into the layer behind. In the inactivated state, as the identical perforation aligns, maximum permeability is achieved. When activated, the deformation of the SMA causes the panel behind to slide up creating an overlapping pattern that reduces the overall permeability. The operation provides an openness factor which ranges between 63% (inactivated) to 39% (activated) (Schneider, et al., 2021).

ADAPTEX Wave, on the other hand, is based on a geometrical deformation of wave-shaped textile bands. The deformation is induced by the SMA wire that is interwoven along the length of the textile bands. As the SMA shrinks, it forces the tape to buckle, enabling an open and closed state comparable to eyelids. The operation states allow the openness factor to be configured within the range of 70% during inactivation and 5% when activated. (Schneider, et al., 2020)

The operating principle of both concepts was investigated by the development of a 1.35 x 2.80 m demonstrator at a 1:1 scale. After implementation and proof of general functionality, they were subjected to various measurements and investigations of their physical performance. In this initial phase of the project, the SMA was activated by the external introduction of an electrical current to manipulate the required temperature change in order to initiate the adaptation mechanism where the SMA length becomes shorter when activated. (Denz et al., 2021). This allowed for both automation and manual control by the user. Later, as in the recent development of the ADAPTEX KLIMA+ project, both solar shading concepts were designed to be completely self-sufficient, without dependency on introduced electrical power, and solely activated by the changes of ambient temperature and irradiation exposure on the textile surfaces.

This passive approach simplifies the system and eliminates previously required technical infrastructure to control and activate the SMA. At the same time, it imposes additional requirements for pre-planning and selecting the suitable SMA for the prevailing temperature range. Since the properties and activation ranges of the SMAs are defined during their production process, ADAPTEX

KLIMA+ sun shading only operates in accordance with the pre-programmed configuration with only minor manipulations allowed. These small manipulations are possible by the adjustment of secondary variables like changing the weight or the strength of the textile, as well as by increasing or reducing the length of the applied SMA. The consideration of the individual needs of different users is neglected in the current development stage ADAPTEX KLIMA+ because the focus is on understanding the behaviour of the SMA and the textile materials. Therefore, the design of the concepts focused on an application of the self-sufficient sunshade for use in public areas, where the need for individual manual control was not part of the requirements.

Operation as a passive solar shading system requires a deep understanding of the textile and SMA material properties. The subtropical and dry climate in Muscat, Oman, provides an ideal environment for the investigation of material behaviours under the extreme alternation of prevailing hot daytime temperatures and relatively cooler night-time temperatures. After initial tests under controlled conditions at the Priedemann Façade-Lab in Berlin shown in FIG 5. , the shading system will be further investigated under real conditions of the outdoor climate in Oman. For this purpose, one ADAPTEX Wave solar shading screen, consisting of three individual elements, and one Mesh screen, consisting of five smaller individual elements were produced to be installed at the Eco House of the German University of Technology in Oman (GUtech) in Muscat as illustrated in FIG 6.

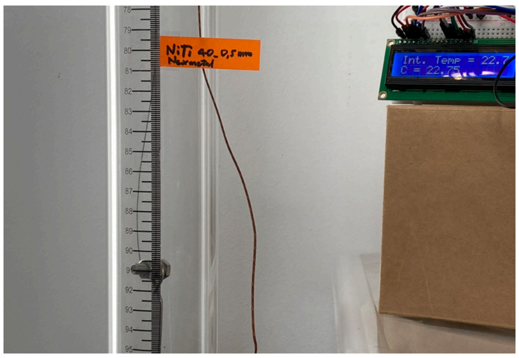

FIG. 5 Testing of the SMA-behavior under maintained and supervised temperature conditions

FIG. 6 Application of the passive ADAPTEX sun shading to the EcoHouse at GUtech in Muscat, Oman

An important aspect of the ADAPTEX application in Oman is the monitoring of the system. The Cyber-Physical system framework has been employed as a mediator to collect comprehensive data on the environmental conditions and on the behaviour of the system in response to occurring changes of the climate. Automation technologies and IoT concepts come into play in this context. Installed as a decentral organized sensor network, the monitoring system takes solar radiation, ambient temperature, as well as wind conditions into account. At the same time, the surface temperatures of the SMA are recorded via thermal coupling sensors at different locations. The reaction of the system is documented via displacement measurements and video recordings. All sensors are connected to different Arduino MKR1010 Wifi microcontrollers, which share their data with the central Raspberry PI 4 broker via wireless network using an MQTT communication protocol. FIG 7. shows the technical setup of the monitoring system.

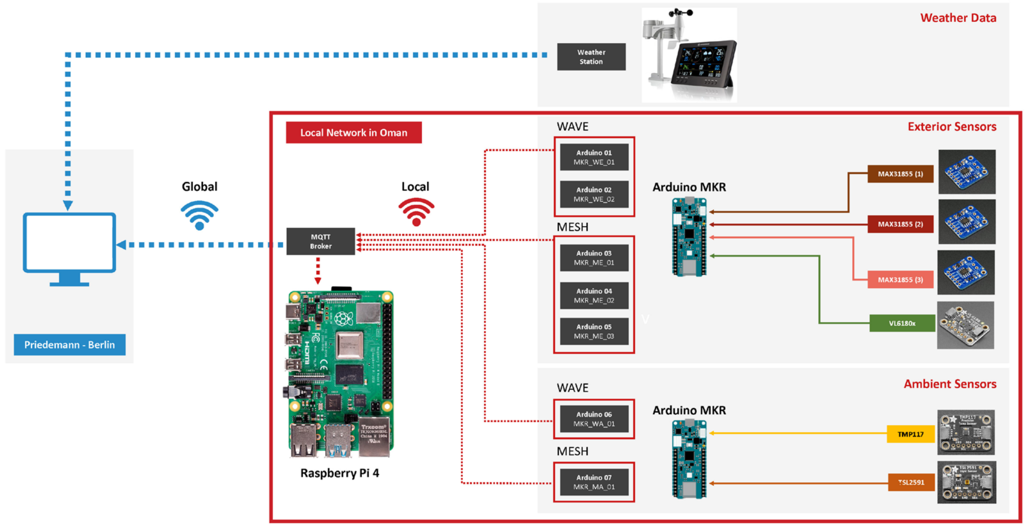

FIG. 7 Decentrally organized sensor network for monitoring the adaptex sunshading in Oman

The Raspberry Pi acts as a broker and connects to the Internet. It enables cloud-based data logging and access to real-time monitoring data remotely. This is crucial to the success of the project, as the prototypes are left unattended most of the time. The monitoring system runs autonomously with external control for maintenance and diagnostics, allowing the collected data to be accessed over the cloud in real time.

5.3 PRÄKLIMA AS ACTIVE APPROACH TO ADAPTIVITY

PRÄKLIMA is a research project, developed to meet the sustainability goals to achieve a near climate neutral building stock by 2050. Together with various partners from both academic and industrial sectors, the formulated objective of the PRÄKLIMA project from the beginning was to develop a modular, multifunctional, adaptive and at the same time, self-sufficient façade system with a predictive-self learning algorithm to control the façade integrated actuators.

PRÄKLIMA is developed as a double skin, unitized façade system with two main elements: an opaque, technical module and a transparent module. To achieve the desired multifunctionality and self-sufficiency, the technical module is incorporated with photovoltaic (PV), LUNOS Nexxt ventilation unit with mechanical ventilation and heat recovery system, as well as a battery for electricity storage. The decentralized LUNOS Nexxt ventilation unit in the opaque element provides air conditioning for heating and cooling. It is positioned behind the photovoltaic (PV) element and takes in the supply air from the cavity space provided for the PV module – thus creating a hybrid air collector. Moreover, a solenoid operated flap has been integrated to control air flow direction into the ventilation system. This allows differentiated control of the ventilation behaviour, depending on seasonal requirements. To efficiently utilize the pre-heated air in winter, it is taken from bottom of the PV panel, and to avoid overheating during summer, the air is taken in from a shorter route from the top of the panel. On the other hand, the transparent module consists of a mechanically operated window that provides natural ventilation, lighting, views to the outside and the use of passive solar gains, which can be controlled by the additional integrated automated venetian blinds. The façade is currently installed according to FIG 8. as a prototype in front of a 2.00 x 3.00 x 3.00 m insulated chamber, which serves as a test stand at SOMMER Fassadensysteme in Hof, Germany. The functionality and performance of the system are investigated using this setup in the ongoing test operation.

FIG. 8 PRÄKLIMA façade in front of the insulated chamber serving as a testbed for ongoing monitoring, the opaque element on the right, the transparent one left side.

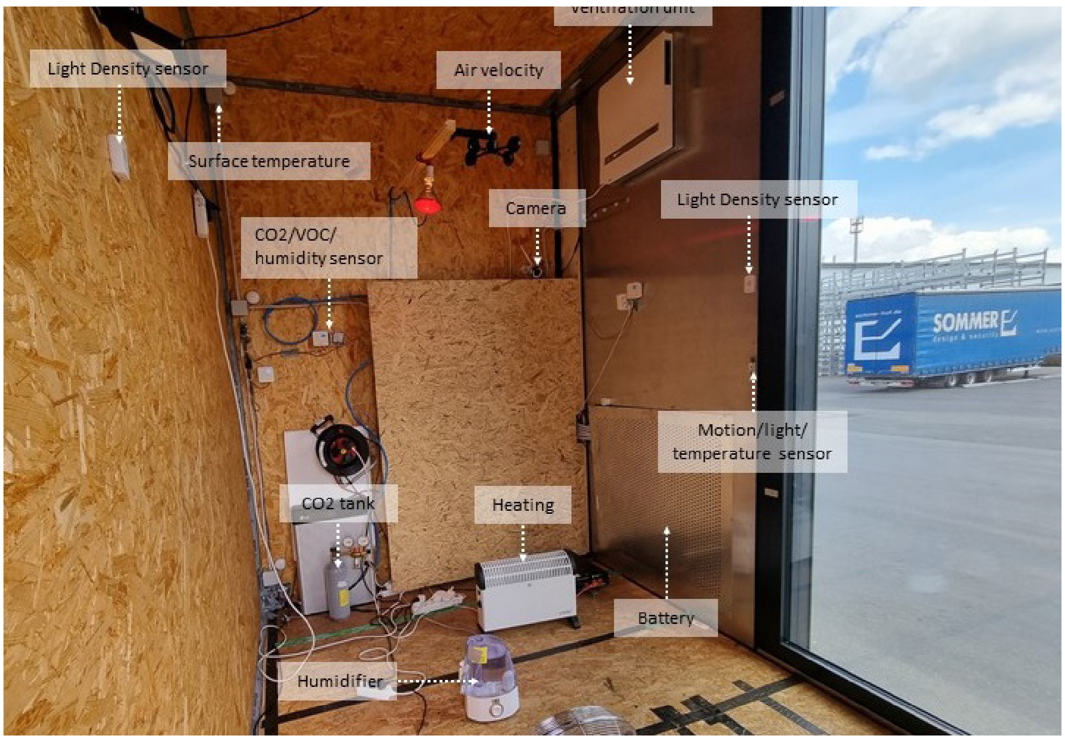

FIG. 9 Interior view of the PRÄKLIMA Testbed highlighting main sensor and actuator devices

Under the Cyber-Physical system framework, the PRÄKLIMA façade incorporates an extensive sensor technology serving as mediators to enable different automated functions, providing for the technical implementation of adaptation strategies. The sensor technology is installed in various locations including inside the test chamber as visible in FIG 9., within the façade element between the cavity, and at the exterior of the façade element in areas that are exposed to environmental influences. The setup considers, among many others, the measurement of wind speed, precipitation, illuminance in the outdoor environment, while for example CO_2, air temperature, motion, and illuminance sensors are deployed inside to provide a meaningful information base on the conditions of the indoor environment.

The name of the PRÄKLIMA project derives from its predictive and adaptive control strategy. An installed Raspberry Pi microcomputer and a small field-programmable gate array (FPGA) form the control unit of the façade and utilize the gathered information from the sensor system by means of a self-learning algorithm that also takes global information like weather forecasts and user behaviour into account. The control concept is illustrated in FIG 10. Based on the information provided, the self-learning algorithm makes independent decisions about the control of the automated façade functions. Because it takes into account previous responses and data, the decision-making regarding the optimal configuration improves during its operational lifetime.

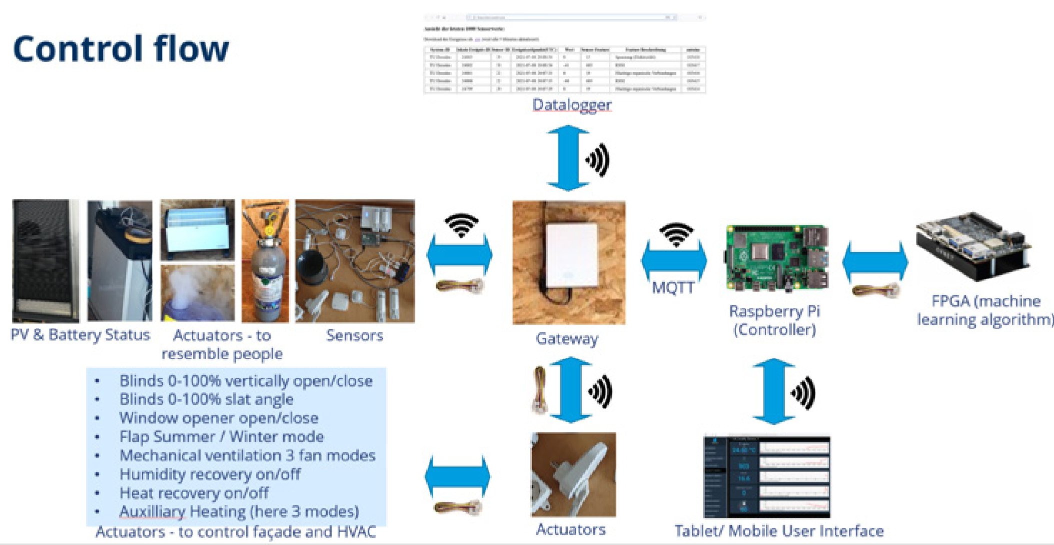

FIG. 10 Control concept of the self-learning PRÄKLIMA façade

Under the objective of a self-sufficient and autarkic operation of the PRÄKLIMA façade, the integrated PV module is a crucial component, as it makes the electrical operation of the technical equipment, such as sensors and automated façade functions, independent of additionally invested energy from the power grid. This ideal complete autarkic operation is not yet fully achieved, as in the preliminary configuration of the prototype the energy consumption of the Lunos Nexxt device exceeds the provided power supply.

6 RESULTS AND DISCUSSION

The ADAPTEX concepts Wave and Mesh, as described in Section 5.2, demonstrate a passive approach to autonomous opening and closing of textile sun shading via integrated shape memory alloys. In the PRÄKLIMA project, extensive automation technologies and a self-learning algorithm were applied in order to enable the adaptivity of the façade. The two case studies exemplarily contrast the passive approach of using smart materials with the active solution through the use of automation technologies and digital control. Both approaches led to functional and effective concepts within the framework of their respective project goals.

6.1 PASSIVE VS. ACTIVE APPROACH

Due to their operational simplicity with minimal components and the absence of high-tech electronic components, passive solutions offer an advantage over active, automated adaptive concepts, which essentially consists of their reduced vulnerability to technical errors as well as their independence of an additional energy supply. Compared to an active control system however passive systems conversely lack control options and overriding possibilities of the adjustment processes during operation. As learned from the ADAPTEX project, the preconfigured material properties are permanent and cannot be adapted to possibly changed requirements. However, the monitoring system in the project, implemented via a decentralized sensor network, has shown promising application possibilities of automation technologies in passive systems with regard to their pre-configuration and for the purpose of their function monitoring during operation. Furthermore, the question arises whether there are possible interfaces between active and passive solutions, after the passive ADAPTEX sun shading concept was initially activated by the supply of electrical energy. Thus, an override of passive adjustment processes by a digital control appears as possible as the inclusion of the SMA as a part of the sensor system of an automated concept. Vice-versa, it also seems possible that the integration of passive adaptation strategies can also be designed as a component of active control systems, as long as their properties and states can be detected during operation and taken into account in the overall control of the façade. In this way of thinking, the passively acting components as resilient actuators with their material-integrated intelligence contribute to the simplicity and resilience of active automated, multifunctional adaptive façades. Thus, the passively operating sun shading solution ADAPTEX could also be integrated into the automation concept of PRÄKLIMA, utilizing the intrinsic capacities of SMA. In this yet hypothetical application, the performance of the shading system can be detected by sensors and coordinated with other actively controlled components such as the ventilation system. If necessary, the non-activated state of the sun shading could be overridden by supplying electrical energy as a secondary mechanism. In this way of thinking, smart materials can become part of actively controlled systems, leading also into desirable further research about the programmability of non-electric systems which is already being pursued in various projects (*Everything under Control*, 2013).

6.2 THE POTENTIAL OF CPFS AS AN ENABLER AND MEDIATOR

The potential of the CPFS system as both an enabler and a mediator has been presented through the development of ADAPTEX and PRÄKLIMA. While in ADAPTEX, the Cyber- Physical system framework has been applied only as a mediator for data collection, the automation concept of the PRÄKLIMA façade project already features broader aspects of a cyber-physical system. This includes comprehensive data collection via extensive sensor technology, wireless communication of data within the system, and the application of a self-learning algorithm in the control of the system. As described in Section 1.3, one of the main aspects of CPS is the flexibility of the system, since the structure no longer follows the hierarchical concept of an automation pyramid, but is based on the decentralized interaction of individual, independently intelligent system components. This opens up a new way of looking at the intelligence of the components itself, where it no longer matters whether it is based on material intelligence or on digital control. On the different levels of the cyber-physical system concept, new interfaces for the interlocking of active and passive components are emerging in the data acquisition of sensor technology, in cyber-control of the system, as well as in the execution of decisive adaptation processes. This approach dissolves the boundaries between previous purely passive or active adaptation concepts by expanding the pool of technologies that can be integrated into the system, thus enabling new design freedom in the configuration of coordinated adaptations. This paves the way for a new generation of universal multifunctional adaptive façade systems.

6.3 THE NEED FOR MODULAR AND FLEXIBLE CONSTRUCTION

Ensuring that shorter-lived components can be reconfigured and replaced contributes to the sustainability of the façade as an overall system, since it is possible to react flexibly to changing requirements without having to replace the entire façade. This is particularly evident in view of the increasing integration of computer and automation technologies with short life spans. Therefore, as defined by Kaelbling (1987), modularity and adaptivity are important aspects of intelligent reactive systems. Therefore, a particular requirement for component exchangeability exists, for which the research into multifunctional plug & play façades provides a possible answer to ensure modularity and reversibility of façade construction (Mach et al., 2015). Cyber-physically automated façades meet this requirement for modularity due to their decentrally organized structure, in which individual components such as sensors or actuators can be removed or modified without compromising the overall operation of the system. The cyber-physical structure of the façade automation also makes an important contribution to the long-lasting usability of the automated façade construction. It enables software updates to be made to adapt the configuration of the structure to changing requirements over the course of its service life, which makes the physical replacement of components obsolete to a certain extent.

7 CONCLUSIONS

In shedding light on the ADAPTEX passive-adaptive concept and the extensive automation in the PRÄKLIMA project, the study concludes possible interfaces that suggest both the use of automation technologies for configuring and monitoring passive adaptation processes and the integration of supposedly passive technologies such as smart materials in active automation concepts. Through the Cyber-Physical system, necessary data points such as ambient conditions, or indoor conditions can be systematically collected. These data can be further analysed, interpreted, and utilizes as the control signal. Due to their decentralized character and control concept, Cyber-Physical Systems can play an important mediating role in the design of corresponding hybrid solutions in the sense of holistically considered, multifunctional adaptive façades, as they allow a high degree of flexibility in the configuration and interaction of the active and passive system components.

Acknowledgements

The projects presented in this scientific paper are the result of close cooperation between various research partners. Acknowledgements belong to the Technische Universität Dresden Institut für Baukonstruktion und Institut für Technische Informatik, SOMMER Fassadensysteme – Stahlbau – Sicherheitstechnik GmbH & Co. KG, and Die Netz-Werker AG for their contributions and cooperation in the project PRÄKLIMA. The project PRÄKLIMA is funded by the BMWK - Zentrales Innovationsprogramm Mittelstand (ZIM). For the project ADAPTEX, the research partners weißensee kunsthochschule berlin, Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU, Carl Stahl ARC GmbH, VERSEIDAG-INDUTEX GmbH, i-Mesh, ITP GmbH and SGS Ingenieurdienstleistungen im Bauwesen GmbH are acknowledged. ADAPTEX is funded by the German Federal Ministry of Education and Research (BMBF) as part of the smart^3 research network.

References

Addington, D. M., Schodek, D., & Schodek, D. L. (2007). *Smart materials and technologies: For the architecture and design professions* (Repr. 2007). Elsevier.

Aelenei, D., Aelenei, L., & Vieira, C. P. (2016). Adaptive Façade: Concept, Applications, Research Questions. *Proceedings of the 4th International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2015)*, *91*, 269–275. https://doi.org/10.1016/j.egypro.2016.06.218

Aelenei, L., Aelenei, D., Romano, R., Mazzucchelli, E., Marcin, B., & Rico-Martinez, J. M. (2018). *Case Studies—Adaptive Façade Network*.

Aksamija, A., (2013). *Sustainable façades: design methods for high-performance building envelopes*. John Wiley & Sons, Inc, Hoboken, New Jersey.

Attia, S., Lioure, R., & Declaude, Q. (2020). Future trends and main concepts of adaptive façade systems. *Energy Science & Engineering*, *8*(9), 3255–3272.

BAFA - Bundesförderung Serielles Sanieren. (2022). Bundesförderung Serielles Sanieren. https://www.bafa.de/DE/Energie/Energieeffizienz/Serielles_Sanieren/serielles_sanieren_node.html

Biesinger, F., Meike, D., Kraß, B., & Weyrich, M. (2019). A digital twin for production planning based on cyber-physical systems: A case study for a cyber-physical system-based creation of a digital twin. In *12th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 18-20 July 2018, Gulf of Naples, Italy* (Bd. 79, S. 355–360). https://doi.org/10.1016/j.procir.2019.02.087

Bonci, A., Carbonari, A., Cucchiarelli, A., Messi, L., Pirani, M., & Vaccarini, M. (2019). A cyber-physical system approach for building efficiency monitoring. *Automation in Construction*, *102*, 68–85. https://doi.org/10.1016/j.autcon.2019.02.010

Broy, M. (2010). Cyber-physical systems—Wissenschaftliche herausforderungen bei der entwicklung. In M. Broy (Hrsg.), *Cyber-physical systems* (S. 17–31). Springer Berlin Heidelberg. http://link.springer.com/10.1007/978-3-642-14901-6_2

Bui, D.-K., Nguyen, T.N., Ghazlan, A., Ngo, N.-T., Ngo, T.D., (2020). Enhancing building energy efficiency by adaptive façade: A computational optimization approach. *Applied Energy 265*, 114797. https://doi.org/10.1016/j.apenergy.2020.114797

Cerf, V. G. (2010). Building Automation. *Interconnecting Smart Objects with Ip: The Next Internet*, 361–372. https://doi.org/10.1016/B978-0-12-375165-2.00024-7

Chaillou, S. (2022). *Artificial Intelligence and Architecture: From Research to Practice*. Birkhäuser. https://doi.org/doi:10.1515/9783035624045

Decker, M., & Zarzycki, A. (2014). *Designing Resilient Buildings with Emergent Materials*. https://doi.org/10.13140/2.1.1060.8967

Domingues, P., Carreira, P., Vieira, R., & Kastner, W. (2016). Building automation systems: Concepts and technology review. *Computer Standards & Interfaces*, *45*, 1–12. https://doi.org/10.1016/j.csi.2015.11.005

Dumitrescu, R., Anacker, H., & Gausemeier, J. (2013). Design framework for the integration of cognitive functions into intelligent technical systems. *Production Engineering*, *7*(1), 111–121. https://doi.org/10.1007/s11740-012-0437-z

EUR-Lex—52020DC0098—EN, Nr. COM/2020/98 final (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX-:52020DC0098&from=EN

Everything under control: Building with biology. (2013). Stichting Archis.

Fox, M. (2016). *Interactive architecture: Adaptive world* (First edition., S. 176). Princeton Architectural Press.

Gupta, G., & Bose, I. (2019). Digital transformation in entrepreneurial firms through information exchange with operating environment. In *Information & Management* (S. 103243). https://doi.org/10.1016/j.im.2019.103243

Hamedani, A. Z., & Huber, F. (2012). A comparative study of DGNB, LEED and BREEAM certificate systems in urban sustainability. *The sustainable city VII: Urban regeneration and sustainability*, *1121*, 121–132.

Hensel, M. (2013). *Performance-oriented architecture: Rethinking architectural design and the built environment*. John Wiley and Sons, Ltd, Publication.

Herterich, M.M., Uebernickel, F., Brenner, W.,(2015). The Impact of Cyber-physical Systems
on Industrial Services in Manufacturing. *Procedia CIRP* 30, 323–328.
https://doi.org/10.1016/j.procir.2015.02.110

Herwan, J., Kano, S., Oleg, R., Sawada, H., & Kasashima, N. (2018). Cyber-physical system architecture for machining production line. In *2018 IEEE industrial cyber-physical systems (ICPS)* (S. 387–391). https://doi.org/10.1109/ICPHYS.2018.8387689

Herzog, T., Krippner, R., & Lang, W. (2004). *Façade construction manual*. Birkhauser-Publishers for Architecture.

IEA. (2021). *Net Zero by 2050—A Roadmap for the Global Energy Sector*. 224.

In focus: Energy efficiency in buildings. (2020). European Commission - European Commission. https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-lut-17_en

Jamaludin, J., & Rohani, J. M. (2018). Cyber-physical system (CPS): State of the art. In *2018 international conference on computing, electronic and electrical engineering (ICE cube)* (S. 1–5). https://doi.org/10.1109/ICECUBE.2018.8610996

Kaelbling, L. P. (1987). An architecture for intelligent reactive systems. Reasoning about
actions and plans, 1(2), 395-410.

Karbasi, A., & Farhadi, A. (2021). A cyber-physical system for building automation and control based on a distributed MPC with an efficient method for communication. *European Journal of Control*, *61*, 151–170. https://doi.org/10.1016/j.ejcon.2021.04.008

Kasinalis, C., Loonen, R. C. G. M., Costola, D., & Hensen, J. L. M. (2014). Framework for assessing the performance potential of seasonally adaptable façades using multi-objective optimization. *Energy and Buildings* (Bd. 79, S. 106–113). https://doi.org/10.1016/j.enbuild.2014.04.045

Konis, K., & Selkowitz, S. (2017). *Effective Daylighting with High-Performance Façades*. Springer International Publishing. https://doi.org/10.1007/978-3-319-39463-3

Kragh, M. K., & Jakica, N. (2022). Circular economy in façades. *Rethinking Building Skins* (S. 519–539). Elsevier. https://doi.org/10.1016/B978-0-12-822477-9.00016-4

Kraus, M. A., & Drass, M. (2020). Artificial intelligence for structural glass engineering applications—Overview, case studies and future potentials. *Glass Structures & Engineering*, *5*(3), 247–285. https://doi.org/10.1007/s40940-020-00132-8

Loonen, R., Rico-Martinez, J. M., Favoino, F., Brzezicki, M., Menezo, C., La Ferla, G., & Aelenei, L. (2015). *Design for façade adaptability: Towards a unified andsystematic characterization*. 10th Conference on Advanced Building Skins, Bern, Switzerland.

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

Luna-Navarro, A., Loonen, R., Juaristi, M., Monge-Barrio, A., Attia, S., & Overend, M. (2020). Occupant-Façade interaction: A review and classification scheme. *Building and Environment*, 106880.

Mach, T., Grobbauer, M., Streicher, W., & Müller, M. J. (Hrsg.). (2015). *mppf—The multifunctional plug&play approach in façade technology*. Verl. der Technischen Univ. Graz.

Maleki, B. A. (2011). *Wind Catcher : Passive and Low Energy Cooling System in Iranian Vernacular Architecture*.

Marchi, L., Antonini, E., & Politi, S. (2021). Green Building Rating Systems (GBRSs). *Encyclopedia*, *1*(4). https://doi.org/10.3390/encyclopedia1040076

Mary Reena, K. E., Theckethil Mathew, A., & Jacob, L. (2015). An Occupancy Based Cyber-Physical System Design for Intelligent Building Automation. *Mathematical Problems in Engineering*, *2015*, 1–15. https://doi.org/10.1155/2015/132182

Menges, A. (2015). The new cyber-physical making in architecture: Computational construction. *Architectural Design* (Bd. 85, S. 28–33). https://doi.org/10.1002/ad.1950

Menges, A., & Reichert, S. (2015). Performative Wood: Physically Programming the Responsive Architecture of the *HygroScope* and HygroSkin Projects: Performative Wood: Physically Programming the Responsive Architecture of the *HygroScope* and HygroSkin Projects. *Architectural Design*, *85*(5), 66–73. https://doi.org/10.1002/ad.1956

Menges, A., Reichert, S., & Krieg, O. D. (2014). Meteorosensitive Architectures. In M. Kretzer & L. Hovestadt (Hrsg.), *ALIVE* (S. 39–42). Ambra Verlag. https://doi.org/10.1515/9783990436684.39

Merz, H., Hansemann, T., & Hubner, C. (2009). Building Automation. *Building Automation*, 1–282. https://doi.org/10.1007/978-3-540-88829-1

Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. *Procedia CIRP* (Bd. 17, S. 9–13). https://doi.org/10.1016/j.procir.2014.03.115

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., & Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals*, *65*(2), 621–641. https://doi.org/10.1016/j.cirp.2016.06.005

Nambisan, S., Wright, M., & Feldman, M. (2019). The digital transformation of innovation and entrepreneurship: Progress, challenges and key themes. *Research Policy*, *48*(8), 103773. https://doi.org/10.1016/j.respol.2019.03.018

Negri, E., Fumagalli, L., & Macchi, M. (2017). A review of the roles of digital twin in CPS-Based production systems. In *27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy* (Bd. 11, S. 939–948). https://doi.org/10.1016/j.promfg.2017.07.198

Pasupathy, A. V., & Velraj, R. (2006). Phase Change Material Based ThermalStorage for Energy Conservation inBuilding Architecture. *International Energy Journal*, *7*(2).

Payne, A. O., & Johnson, J. K. (2013). Firefly: Interactive Prototypes for Architectural Design. *Architectural Design*, *83*(2), 144–147. https://doi.org/10.1002/ad.1573

Pisching, M. A., Junqueira, F., Filho, D. J. d. S., & Miyagi, P. E. (2016). An architecture based on IoT and CPS to organize and locate services. In *2016 IEEE 21st international conference on emerging technologies and factory automation (ETFA)* (S. 1–4). IEEE. https://doi.org/10.1109/ETFA.2016.7733506

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

Rajkumar, R., Lee, I., Sha, L., & Stankovic, J. (2010). Cyber-physical systems: The next computing revolution. In *Proceedings—Design automation conference* (S. 731–736). https://doi.org/10.1145/1837274.1837461

Sandak, A., Sandak, J., Brzezicki, M., & Kutnar, A. (2019). State of the Art in Building Façades. In A. Sandak, J. Sandak, M. Brzezicki, & A. Kutnar (Hrsg.), *Bio-based Building Skin* (S. 1–26). Springer Singapore.

Shi, L., Pouramini, S., (2022). Adaptive façade for building energy efficiency improvement by

arithmetical optimization algorithm. Concurrency and Computation. https://doi.org/10.1002/cpe.7152

Soucek, S., & Loy, D. (2007). Vertical integration in building automation systems. *2016 Ieee 14th International Conference on Industrial Informatics (Indin)*, 81–86. https://doi.org/Doi 10.1109/Indin.2007.4384735

Schneider, M., Waldhör, E.F., Denz, P.-R., Vongsingha, P., Suwannapruk, N., Sauer, C.,

(2021). Adaptive Textile Façades Through the Integration of Shape Memory Alloy. Presented at the ACADIA 2020 - Distributed Proximities.

United Nations Department of Economic and Social Affairs. (2021). *The Sustainable Development Goals Report 2021*. https://www.unilibrary.org/content/books/9789210056083

Wang, X., Xi, Q., & Ma, Q. (2021). A review of current work in research of Trombe walls. *E3S Web of Conferences*, *248*, 03025. https://doi.org/10.1051/e3sconf/202124803025

Wolf, M. (2012). Embedded computing. *Computers as components* (S. 1–50). Elsevier.