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Prototype of a cyber-physical façade system

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ABSTRACT

This research examines the technical feasibility of façades as cyber-physical systems, which can revolutionize former hierarchical and closed automation concepts of mechatronics through their cooperation of decentralized entities. While such systems are already employed in many application fields to increase the flexibility and performance of automated processes, a transfer to the operation of automated adaptive façades has not yet been investigated. In this study, a prototype is developed to systematically test the application of individual cyber-physical system criteria to façades. The prototype is organized in modules, each of which represents one instance of the selected façade functions of solar shading, natural and mechanical ventilation, and heating and cooling. The emphasis lies on development of a communication system that allows the functions to communicate and cooperate with each other. Evaluation of the prototype takes place in five independent case studies, in which the potential of the cyber-physical implementation is demonstrated by a successful system-internal cooperation. The study found that important aspects of cyber-physical systems, like their embedded control, the integration of actuators and sensor networks, implementation of a communication system and connection to a digital twin, are also feasible and promising in the façade domain.

1. Introduction

1.1. Background

Within the current, ongoing digitalisation a transition towards ubiquitous computation and the comprehensive networking of our environment into an Internet of Things (IOT) takes place [1]. In this context, cyber-physical systems (CPS) are significantly changing the design concept of automated applications [2]. Due to very heterogeneous approaches in different fields of application, cyber-physical systems are not clearly defined, but described by possibly fulfilled criteria [3]. In general, this includes that cyber-physical systems are based on the close integration of physical devices with their digital control. In contrast to former hierarchical and rule-based automation concepts, CPSs are deeply embedded and decentrally organized [4,5]. This requires the system components to comprise an individual computing capacity and to collaborate in real time on the basis of sensor collected data. According to Lee [6], the networking of the components is a core aspect in the transformation of embedded systems into cyber-physical ones. Wang et al. [3] identify other important properties of such systems, such as their autonomy without the need for continuous human observation, their cross-domain application, and their vertical integration throughout different levels of the system hierarchy. CPSs operate in unpredictable environments. They must be reliable and robust in dealing with unexpected conditions [6].

Cyber-physical systems are already employed in many application domains. Examples are autonomous transport systems, smart energy supplies, and robotic surgery [4]. In the industry, the implementation of such systems leads to a new development stage, the so-called fourth industrial revolution, also known as Industry 4.0. In the related smart factories, cooperating production facilities form intelligent technical systems with regard to a common production goal [7]. The individual production assets of these systems exchange information via a machine-to-machine (M2M) communication network described by Xu et al. [8] and Verma et al. [9]. Their networking offers a great potential for the flexibility within manufacturing processes as well as for productivity. In the application case of intelligent technical systems, further specific criteria of cyber-physical systems can be identified. These include, for example, the interconnection to a digital twin described by Negri et al. [10] and Kritzinger et al. [11], which enables both monitoring and optimisation of production processes via digital simu-

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lations. The development of cyber-physical systems is still in the beginning stage in the industry, as well. However, methods and reference models for the design of CPSs already exist in this domain, like the level architectures introduced by Lee et al. [12] and Herwan et al. [13].

Façades have a decisive influence on a building's overall performance. In view of desired energy savings and the high expectations towards interior comfort, they must provide the highest efficiency possible. Façades constitute technical systems of different components and material layers. In the interaction of the components they fulfil a multitude of different functions, listed by Klein [14]. Similar to the above described cyber-physical systems, façades operate in dynamic environments with unpredictable constellations of different environmental boundary conditions and interior comfort requirements. Adaptive solutions aim to actively compensate these dynamics by adjusting flexible parts of their construction. In this context, Moloney [15] and Loonen et al. [16] call for holistic concepts against individual adaptive elements. The implementation of such holistic systems requires the coordination of the individual measures. With regard to possible contradictions in the fulfilment of opposing façade functions, information-based negotiations and correspondingly coordinated adaptations are required.

According to Böke et al. [17], instead of using smart materials as described by Drossel et al. [18] and Ritter [19], façade adaptations are mainly carried out by the use of automation technologies. Especially in buildings with high proportions of glazing, automation can contribute to the building performance. Many façade projects therefore comprise automation technologies as part of the overreaching Building Automation System (BAS). In building practice, there are various technology platforms on which BAS's are implemented, including KNX, LonWorks, BacNet, ZigBee or Z-Wave [20]. Contrary to cyber-physical systems, automation concepts existing today in the building sector are primarily based on centralized controls with predefined rules and a hierarchical structure according to the automation pyramid presented by Merz et al. [21]. However, with generally available processing systems as well as with installed sensors and actuators, recent façades already encompass the main features of mechatronic systems.

This provides comparable conditions for the implementation of cyber-physical systems in the field of façade applications to those in the industry. Böke et al. [22] consider this possibility of cyber-physical façade systems, in which adaptive façade functions are decentrally controlled due to individually embedded computing capacities. They identify a range of active façade functions that can be considered as entities of such a system. Similar to the networked production facilities, as described above, the different automated façade functions could cooperate with each other and thus contribute by flexible and coordinated adaptations to the performance of the façade as an overall system.

1.2. Problem statement

Cyber-physical systems become applied in many application fields, such as in the production facilities of Industry 4.0. However, the structure and technical feasibility of the façade as a cyber-physical system has not yet been examined. There is a lack of knowledge about whether the implementation of the façade as a cyber-physical system is possible and how such a system can be designed in principle. Since many building envelopes are already equipped with extensive automation technology, this study is based on the hypothesis that façades can be technically implemented as cyber-physical systems. It is assumed that essential features such as an embedded and decentral controlled organisation of the façade components as well as the wireless communication between automated entities can also be realised in the façade.

1.3 Objectives

The aim of this study is to examine the structure and technical feasibility of a cyber-physical façade system. In this first approach, a possible architecture of such a façade system will therefore be developed by the means of a prototype, to which essential characteristics of cyber-physical systems are applied. Considered characteristics include the embedding of controls in individual façade functions as formulated by Wolf [23], and their decentralized organisation. The functions are also equipped with relevant sensors and actuators and enabled to perform real-time adaptations on the basis of gathered information. A focus of the investigation is on the communication and cooperation of the automated façade functions. One main objective is therefore the visualisation of possible networked adaptation processes in the interaction of a cyber-physical overall system. Corresponding to the example of cyber-physical systems in Industry 4.0, a digital twin will be developed. Connected to the communication of the façade, it is intended to monitor all adaptation processes.

1.4 Research question

The study is subject to the research question: Can façades be implemented as cyber-physical systems?

The main question is answered by the investigation of implementable characteristics of cyber-physical systems in the following sub-questions:

- Can automated adaptive façade functions be decentrally organized in an overall system architecture?
- Is it possible to embed all façade functions with independent controls and feedback loops?
- Can sensors and actuators be integrated into the functions?
- Can individual façade functions be enabled to communicate and thus cooperate with each other?
- Are the façade functions able to adapt in real-time?
- Is it possible to develop a digital twin to which the physical façade system is connected?

2. Methodology

2.1. General concept

The investigation is based on the experimental development of a modular prototype according to Fig. 1. The prototype consists of individual frame elements that are mounted together to form a complete system. The modularity illustrates the decentralized organisation of the system, in which each module represents one instance of an automated adaptive façade function. The selection of façade functions is based on the findings by Böke et al. [17]. In their study, office buildings in Germany were examined with regard to the automated and adaptive implementation of the façade. In construction practice, there are performance-relevant façade functions that are frequently and comprehensively implemented in an automated manner. Böke et al. [17] identify the sun-related functions solar shading, glare protection, daylight control and light deflection, as well as ventilation, and the support functions heating and cooling. Since these façade-implemented functions are often jointly automated, testing their networkability in a prototype is particularly promising. Against this background, the three functions sun protection, ventilation and heating and cooling are selected for consideration in the prototype, whereby ventilation is implemented as both natural and mechanical ventilation. The prototype is developed following the concept of ontology as described by Gruber [24], which is not about the specific implementation of automated façade functions, but rather about their exemplary attributes and correlations. Although the prototype depicts the façade

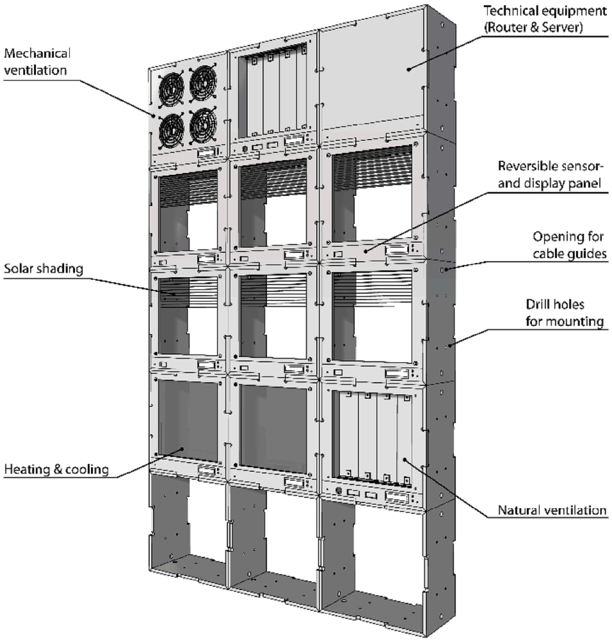


Fig. 1. Concept scheme based on a 3D model of the cyber-physical façade prototype in Rhinoceros 6.

in an abstracted manner and does not represent a 1:1 translation, the arrangement of the modules is based on the layout of real façade constructions. In the lower area, one natural ventilation module and two instances of the façade function heating and cooling are located. The façade function sun protection is realised six times in the middle section. At the top level, two modules illustrate mechanical and natural ventilation. Care was taken during the selection and composition of the façade functions to ensure that the prototype could represent versatile relationships of different scenarios. The orientation of the prototype becomes clear by the one-sided cover element of the modules. The covered side is oriented toward the outside of the façade, while the inside of the building is represented by the opposite, open side.

2.2. Representation of the automated adaptive façade functions

The functions and their adaptation processes are visualised by means of different reactive components, which are oriented to the products used in construction practice. For the visual evaluation of the prototype, the selection of the components depends on the visibility of their states, and not on their actual physical performance. The automation of the prototype is realised on the Arduino platform, which is versatile in terms of the number of available components, sensors, actuators and libraries and which is, at the same time, easily accessible. Each instance of a façade function is equipped with an input, processing and output system as formulated by Moloney [15].

The input system is based on different sensors that are exemplarily assigned to the modules according to the information requirements of the respective façade function. They provide the system with information about the external and internal environmental boundary conditions. Light, gas, temperature, humidity and acoustic sensors are used. The equipment is able to demonstrate a principle operation of the intelligent technical façade system and may be supplemented or modified. For this purpose, not necessarily all sensor data built into the system is used in the feedback loops in order to maintain the proportion between programming effort and significance of the investigation. For the data collection, a distinction is made between sensors oriented toward the outside, as shown in Fig. 2, and those oriented toward the inside. Each module is embedded according to the integration of an associated NodeMCU V2 Amica micro controller as shown in Fig. 3. They process the data collected by the sensors and transfer it into a reaction of the actuators. The micro controllers also establish the wireless networking of the modules as a core aspect of the prototype. They are responsible for sharing the functions-acquired sensor data and actual status with the communication system and, in return, also process the data received from it. The NodeMCU micro controller was therefore chosen because of its integrated ESP8266 ESP12- E Wi-Fi module. The output systems of the functions include the actuators, which carry out the physical adaptation mechanism, and components for the visual representation of information. I2C LCD displays show the most relevant data of each module and help to evaluate the prototype by enabling the comparison with the data collected in the cloud. LEDs visualize the communication of the modules by flashing a RX-LED in case of received messages and a TX-LED in case of sent messages.

Fig. 2. The front of the prototype with visible sensors, LCD displays and LEDs.

Fig. 4 shows the detailed layout of the system with all introduced components. As all modules provide the same processing system based on the NodeMcu microcontroller, the following breakdown of the specific functions configuration only focuses on physical devices, sensors and actuators:

The sun shading is implemented by ready-to-use venetian blinds that are equipped with 28BYJ-48 stepper motors to carry out the possible up and down movement. Also, SG90 micro-servo motors are integrated into the mechanism of the blinds to enable the automated opening by rotation of the blinds. As the functions input system, a photo resistor measures the incident light on the outside of the façade. The planned use of a 2nd light sensor installed on the inside of the

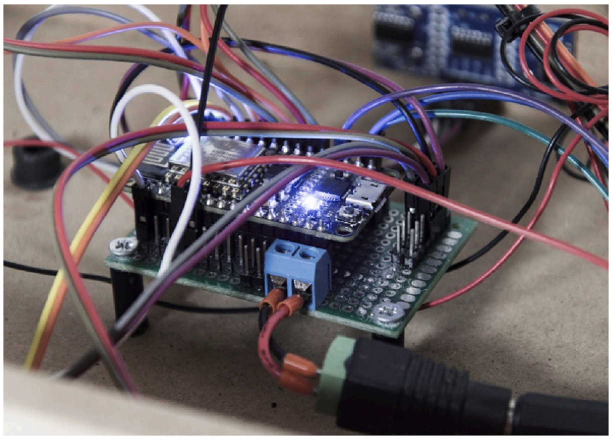


Fig. 3. Close-up of the NodeMCU V2 Amica micro controller installed on a circuit board.

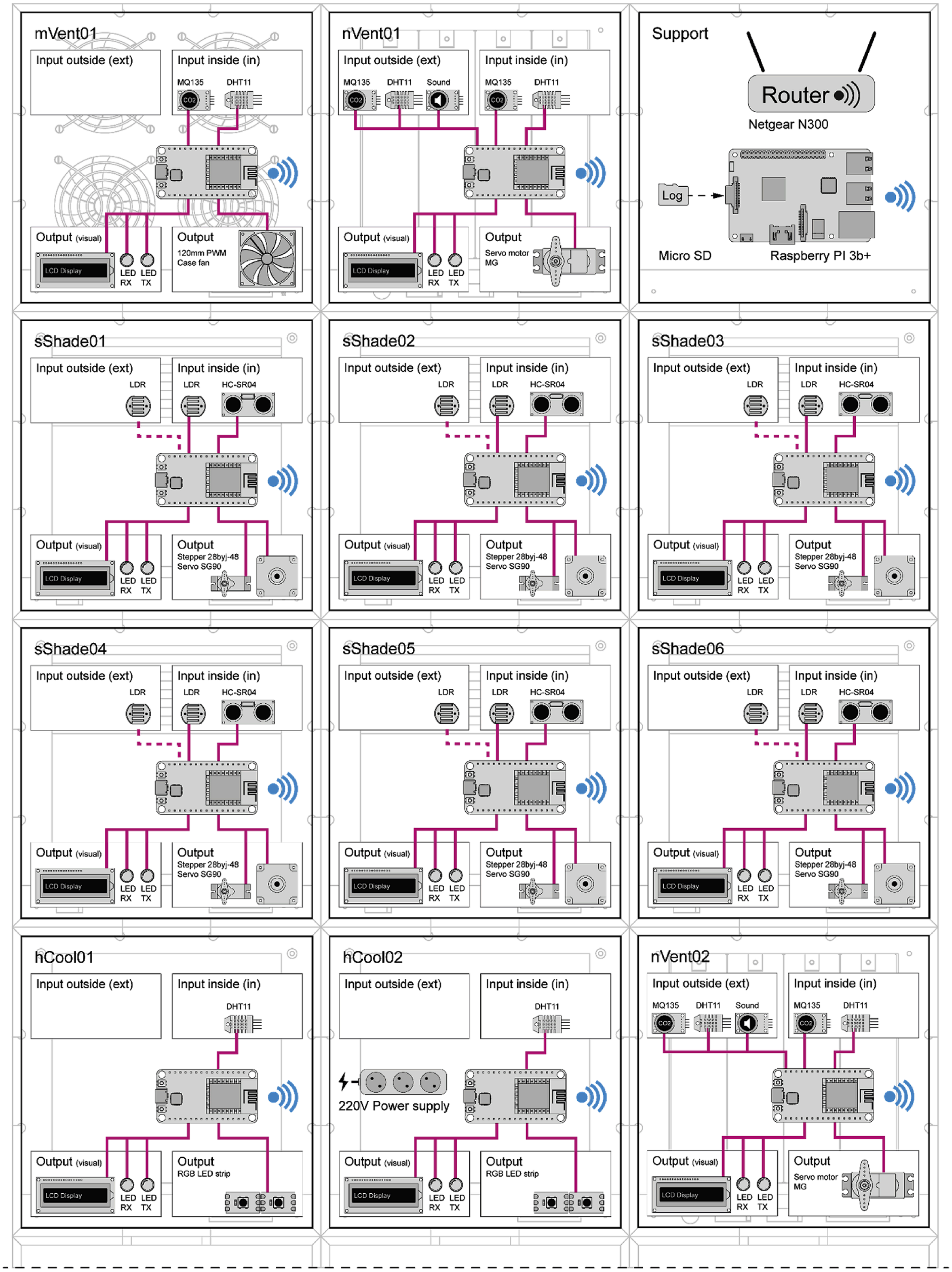


Fig. 4. Technical equipment of the prototype.

modules was omitted during the development process due to limited microcontroller connections.

Most sensors are installed in the natural ventilation modules. Temperature, humidity and air quality are measured both inside and outside. A noise sensor is installed on the outside, as well. The function itself is represented by movable ventilation flaps. They are equipped with a gear mechanism driven by a MG996R servo motor to automatically open and close the flaps. In mechanical ventilation, sensor data on temperature, humidity and air quality are collected. Four 120 mm computer fans are used as actuators. In addition to both possible states “on” or “off”, they express the load of the ventilation system by adjustable fan speeds.

A temperature sensor measures the interior temperature in the heating and cooling modules. The function is demonstrated by RGB-LED lighting, which reflects the status of the convectors by red lighting for heating and blue lighting for cooling. Intensities are represented by the brightness and saturation of the illumination in the respective state.

2.3. Modular and demountable design

Besides robustness and adaptivity, Kaelbling [25] defines modularity as an important aspect of intelligent reactive systems, which, in his estimation, should consist of small, understandable parts. In practice, static structures, moving components and high-tech electronics are subject to very different life cycles. Against this background, the modular structure of the prototype is continued down to the individual parts of the implemented façade functions. The load-bearing structure, here the frames, are firmly fixed. All mechanically movable, kinetic components are reversibly mounted. The same applies to sensors, actuators, microcontrollers and other electronic components. They can be removed and replaced at any time via plug-in, screw and clamp connections.

2.4. Power supply

The modules are supplied with electricity by a central 5 V/20 A power supply unit. Grouped according to their function, the modules can be switched on and off by toggles. Due to their central role in the overall system and their requirements for a uniform electricity flow, the router and the Raspberry Pi 3b + server are connected separately. The computer fans of the mechanical ventilation function require a higher voltage and are therefore also supplied by a separate 12 V adapter. The microcontroller of the function is connected to this power supply via a step-down module.

2.5. Implementation of the communication system

Cyber-physical systems are based on the cooperation of decentralized and networked system components. As the investigation focuses on this possible communication and cooperation of individual façade functions, the integration of a communication system for the exchange of information between the units is of central importance. A connection to the Internet is possible, but not mandatory for an internal system communication [3]. In this study, a connection to the global Internet is neglected and wireless communication only takes place within the developed system.

Topologies describe the organisational structure of a network. Depending on the composition of the individual components, a distinction is made, for example, between point-to-point, tree, or mesh topologies. In the industrial networking of production plants described in the introduction, as well as in building automation, mesh topologies are preferred today due to their higher reliability. In awareness that such more flexible and robust organisational forms are possible, a choice was made for the use of the star topology illustrated in Fig. 5. It is easier to implement and still basically demonstrates the communication capabilities of automated façade functions. A router is firmly integrated into the system and establishes an independent wireless local area network (WLAN) based on the IEEE 802.11 standard. The façade modules communicate in this network using the Message Queuing Telemetry Transport (MQTT) protocol.

MQTT is a lightweight messaging protocol for machine-to-machine (M2M) communication and is used in many Internet of Things applications. The protocol was chosen because of the publish-subscribe strategy with possible one-to-one and one-to-many connections. Another reason for using MQTT was the performance regarding transmission times, which is twice as fast compared to other protocols [27]. Three quality of service (QOS) levels are possible. Due to the

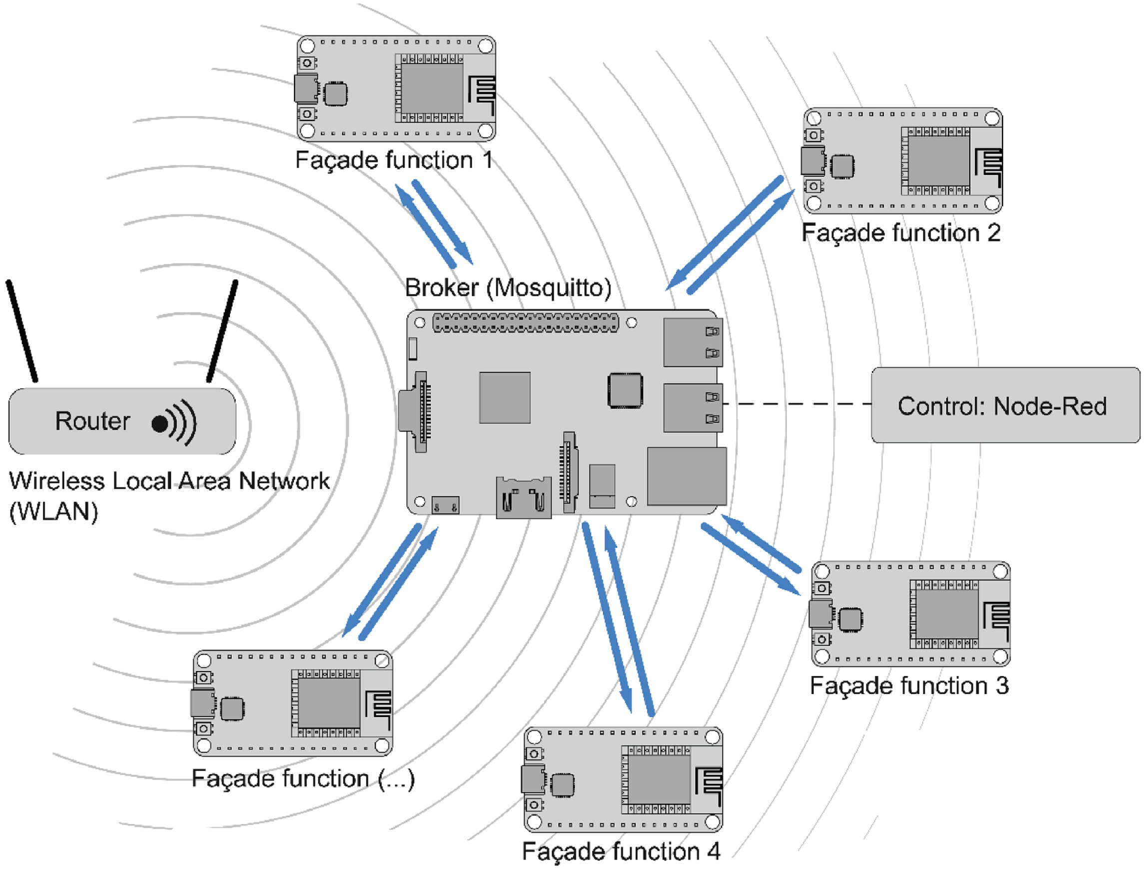


Fig. 5. Organisation of the MQTT communication system derived from Joncas [26].

balance between reliability and performance in data exchange, QOS Level 1 was selected for most messages within the prototype. This ensures the delivery of a message at least once and confirms its receipt by a Puback-reply from the subscriber [28].

The broker forwards all messages sent by the system. It is realised as an open-source Mosquitto server installed on a Raspberry Pi 3b+, mounted in the prototype next to the router. The broker plays an important role for the system, as all messages are passed through it and the communication collapses in the event of a failure. In this case, the system is programmed in such a way that the individual façade functions fall back on their feedback loops described in section 2.5 [29].

The communication between the façade functions is organized in topics. Each function can subscribe to topics and share information within them. The topics are structured hierarchically on three levels. The first level defines the information's affiliation with a classification into sensor, actuator, and status or target value. The second level contains the identity of the addressed façade function. On the third level, a specification is used to uniquely assign a component or value. The topic for the control of the fans in the mechanical ventilation function is, for instance: actuator/mVent01/fanControl. The communication in form of published and received messages is indicated by flashing of the installed respective LEDs.

2.6. Control logic

As visible in Fig. 6, the control of the prototype is organized in two levels. The programming uploaded to the microcontrollers represents the lower control level as formulated by Dumitrescu et al. [7]. It incorporates a local and independent feedback loop on which the instances of a façade functions operate. On the higher control level, the prototype is managed as an overall structure and connections between the modules are established. This is achieved by negotiating sent data in the private cloud of the system. The following section describes how the feedback loops of the different functions work and how they are interconnected on the higher control level.

2.6.1. Lower control level

The flaps of the natural ventilation can be in the positions open, closed and half-open. In the feedback loop, only the states open and closed are used. If the interior temperature or the CO2 level exceed a predefined and changeable global threshold value, the ventilation flaps open by actuating the servo motor. The control system also incorporates data from the noise sensor, which prevents the flaps from opening in the event of a measured noise load. The mechanical ventilation is based on the sensor data of the interior temperature. As with the natural ventilation, the measured value is compared with a target value. If this is exceeded, the mechanical ventilation is activated by a relay. The difference between both values is converted to the fan speed with a defined upper limit. The set speed demonstrates the intensity of ventilation.

The heating and cooling function also works by comparing the measured internal temperature with a desired temperature. If the temperature is too high, cooling of the convectors, shown in blue, is initiated. In the opposite case, the heating mode, visualised in red, is started. The intensity of the illumination increases by adjusting the saturation and brightness of the LEDs proportional to the deviation of the measured temperature to the target.

The measuring range of the installed light sensor is divided into three levels for controlling the sun shading: The upper range is used to detect direct sunlight to which the system reacts by lowering and closing the blinds. The middle range indicates indirect daylight, in which the blind moves down and remains open. The lower range marks the barrier to darkness. In this case, the blind raises if it is not already in the up position. In addition, the three upper modules of the sun protection function are equipped with distance sensors that detect the presence of a possible user. In case of the closed state of the blind, opening is initiated as a reaction to a user's presence. In order to avoid continuous adjustments, a scheduled blocking of the function after triggering is integrated.

2.6.2. Higher control level

On the higher control level, the exchange of information and the interaction between the feedback loops of the individual façade functions takes place. The behaviour of the system results from the defini-

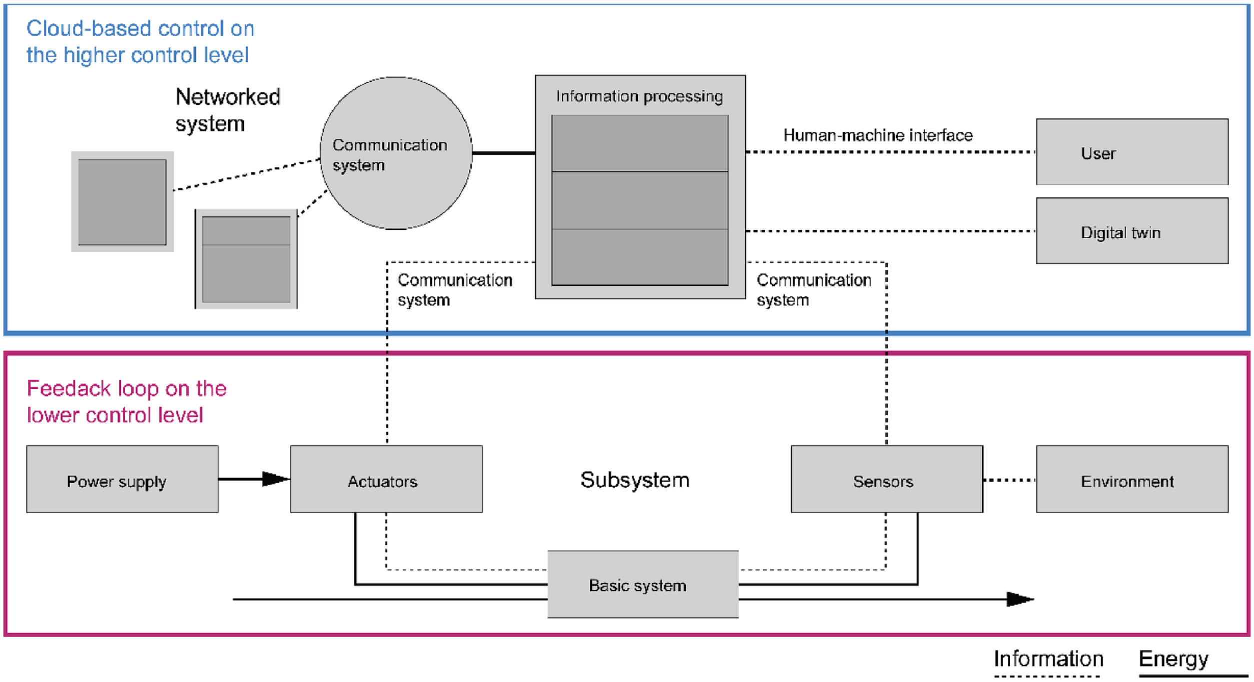


Fig. 6. Structure of the control strategy derived from Dumitrescu et al. [7].

tion of interrelationships, determining which information is to be exchanged between certain façade functions. In the development of the prototype, Node-RED is used for this orchestration of the system. It is a browser based visual programming tool in which dependencies between the systems components can be mapped in the form of flowcharts. A flow consists of individual functions that are represented graphically as nodes. The nodes can receive data, process it and forward the processed data. The stream of information is established by connecting lines between the nodes. All sensor data collected by the different façade functions are sent via the communication protocol and can be used for cross-functional calculations in Node-RED. In the event of carried out adaptations, each function also shares its current configuration state. The control of the prototype is organized in parallel flows. One flow links received information with the user interface, another flow stores all data in a log file and another one defines dependencies between the façade functions. The program can be used not only to process information from the system, but also to generate new information. This enables the definition of new values such as the globally defined target temperature.

For the prototype, first exemplary dependencies are defined with regard to the evaluation in section 3. Fig. 7 shows the flow for the implementation of joint decisions of the six sun shading modules documented in test 5. All actuator states are received via the MQTT theme “actuator” with the assigned wildcard "#". A delay prevents an immediate resetting of a currently set deviation. The actual adjustment between the function states is defined as an independent function in the Java programming language. A key is used to filter out the status information of the sunshade modules from the remaining system data. They are compared with each other and, in the event of a different state, overwritten with the configuration of the other modules. As shown in Fig. 7 on the right, all sun protection modules are entered as recipients of the overwriting.

2.7. User interaction

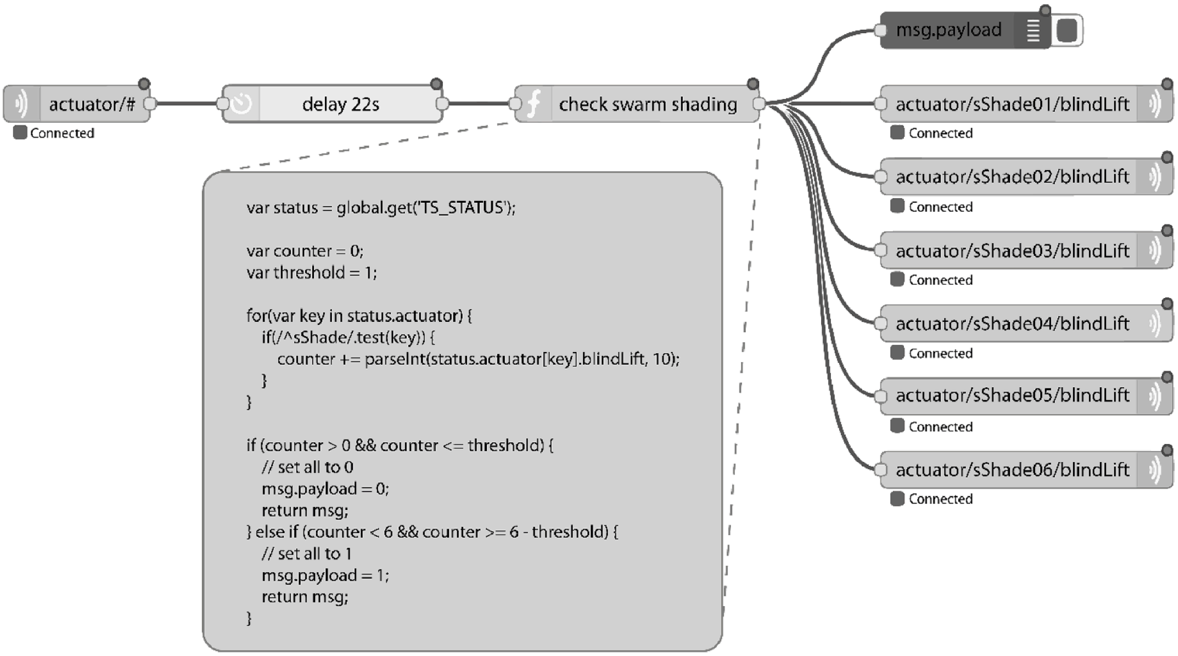
Users with the appropriate permissions have access to the control system via WLAN-capable terminal devices. They can monitor and overwrite the automatic system with individual settings. This is both possible via an MQTT-enabled app as well as over the Internet browser by accessing the Node-RED dashboard. The dashboard can be found under the server IP address with the addition “/ui”. In the prototype, the pre-defined setting options include specifications such as the target temperature of the interior and the direct control of the different automated functions.

2.8. Digital twin

A digital twin generally means the virtual representation of a physical system. It enables the monitoring, real-time optimisations, decision-making and predictive maintenance of the system [10]. In the industry, first software solutions exist for creating digital twins. However, such software for the application of cyber-physical systems on façades does not yet exist. In this study a digital twin is programmed in the development environment “Processing” to monitor the adaptation and communication processes of the prototype. Processing is a Java-based programming language and was developed for screen-based content. The digital twin communicates with the façade functions via the MQTT protocol as client of the network system. It subscribes to the topics of sensor data and actuator states and illustrates the three-dimensional prototype geometry with the processes of coordinated adaptations in real time. It operates on a computer connected to the prototype system. The geometry is loaded into the program as a 3D model in object format (.obj). The motion capabilities are generated by programming according to the physical components of the prototype. In addition to the three-dimensional representation, the recorded sensor data and the states of the individual components are also represented in text form in the digital twin for process monitoring.

2.9. Evaluation

The successfully implemented characteristics of a cyber-physical system as formulated in the research questions in section 1.4 is reflected by the demonstrable capabilities of the prototype. The prototype result and the communication of its façade functions are therefore evaluated qualitatively and visually in five different functional tests. The tests were strategically selected to verify individual features. With regard to sub-questions 1–3, the first test evaluates the ba-



```
var status = global.get('TS_STATUS');

var counter = 0;
var threshold = 1;

for(var key in status.actuator) {
   if(/^sShade/.test(key)) {
      counter += parseInt(status.actuator[key].blindLift, 10);
   }
}

if (counter > 0 && counter <= threshold) {
   // set all to 0
   msg.payload = 0;
   return msg;
} else if (counter < 6 && counter >= 6 - threshold) {
   // set all to 1
   msg.payload = 1;
   return msg;
}
```

Fig. 7. Example flow comparing all solar shading adaptations to perform joint decisions.

sic operability of the modules and the communication system. As examples of possible cooperation, the subsequent tests demonstrate the potential of an internal façade communication, addressed in sub-question 4. This includes the coupling of different façade functions adaptations in tests 2 and 3, the cross-functional use of sensor data in test 4 and the possibility of joint decisions investigated in test 5, which lead to an overwriting of individual feedback loops as a result of a comparison at the higher control level. All tests reflect the real-time adaptation of the modules addressed in sub-question 5, while tests 1 and 3 also consider the connection to a digital twin formulated in the last sub-question.

Table 1 shows the log of the tests performed. The first test is performed and documented only once as a general operational test. All other tests are performed at least three times to eliminate random phenomena and to ensure the robustness of the adaptation processes investigated. The tests are documented in a video file, which is also referenced in Table 1. In the videos, the iterations of the respective examination are introduced by the corresponding number. The digital twin runs parallel to the physical prototype during the entire evaluation. Due to different focal points in the individual tests, it is only part of the video documentation of tests 1 and 3.

3. Results

The prototype was successfully realised, as shown in (video1 and) Figs. 8–10. As soon as it is connected to a power supply, the router sets up a WLAN network in which both the Raspberry Pi as server and the individual modules as clients dial in. An auto-start function launches the server on the Raspberry Pi and enables the node-based control as well as the Node-RED dashboard as user interface. The different tests of this investigation are carried out in this operating state. The following sections describe the performed tests and their results.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jobe.2020.101397

3.1. Test 1 - Reaction of the system to a changing global variable

In the first test, the basic functionality of the communication system and the feedback loops of the façade functions are demonstrated. For this purpose, the target temperature is changed in the system's user interface. The functions of natural and mechanical ventilation as well as heating and cooling are subscribers of this information. The documentation as illustrated in (video2) Fig. 11 shows the physical prototype on the left, the user interface as a screenshot on the top right and the digital twin on the bottom right. The individual functions react to the received information by real-time adaptations based on their individual feedback loops. They confirm their successful adaptation by sending the new configuration state. The digital twin receives both the sensor data sent by the functions and the status information of the individual modules. It maps adaptations synchronously to the physical structure in text-based form and as a three-dimensional model. As result for the research questions in section 1.4, the test verifies the successful integration of sensors and actuators in the automated façade modules and their possible adaptations in real-time. The operational test also demonstrates the possible connection to a digital twin as formulated in sub-question 4.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jobe.2020.101397

3.2. Test 2 - Communication between façade functions

In the second test, the functions natural ventilation (nVent01) and mechanical ventilation (mVent01) are used to investigate the communication system with regard to networked adaptation processes. The sensors of function nVent01 detects possible noise pollution in the outdoor environment of the building. In order to avoid continuous adjustments due to individual impulses and incorrect measurements, the feedback loop has a time delay and only reacts to multiple measurements of the sensor. In response to detected noise, the natural ventilation flaps close. The module shares this new configuration state with the system and triggers the activation of mechanical ventilation. Keeping a programmed time delay, the flaps open as soon as the noise pollution has subsided. The communication system now initiates the deactivation of the mechanical ventilation. The mechanism is demonstrated in the test by a sound file played from a smartphone as illustrated in (video3) Fig. 12. The test confirms real-time adaptations of the system formulated in sub-questions 4 and 5, including communication between the modules.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jobe.2020.101397

3.3. Test 3 - Combined actions

According to the principle formulated in section 3.2, more complex coordination between the façade functions is possible, as well. The test demonstrates a possible interaction between natural ventilation, mechanical ventilation and the heating and cooling system. The starting point for this test is a conceptual scenario in which the energy consumption for HVAC is to be saved when natural ventilation is open. The state of both natural ventilation systems is recorded on the cloud-based control level. As soon as one of the modules is open, this state leads to a deactivation of the mechanical ventilation and the convectors. Only after the ventilation flaps have been closed both functions are enabled via the communication system and fall back into their automated feedback loop (Video4). Fig. 13 represents an excerpt of the video documentation, showing the physical prototype on the left and the digital twin on the right. The test underlines the possi-

Table 1
Protocol of the performed tests.

Test #	Description	Test execution 1		Test execution 2		Test execution 3		Related video
		Physical model	Digital twin	Physical model	Digital twin	Physical model	Digital twin	
Test 1	Reaction of the system to a changing global variable	✓	✓	×	×	×	×	Documentation1_ Reaction of the system to a changing global variable.mpeg
Test 2	Communication between façade functions	✓	×	✓	×	✓	×	Documentation2_ Communication between façade functions.mpeg
Test 3	Combined actions	✓	✓	✓	✓	✓	✓	Documentation3_ Combined actions .mpeg
Test 4	Shared sensor information	✓	×	✓	×	✓	×	Documentation4_ Shared sensor information.mpeg
Test 5	Collaborative decisions	✓	×	✓	×	✓	×	Documentation5_ Collaborative decisions.mpeg

Fig. 8. Front view of the realised prototype.

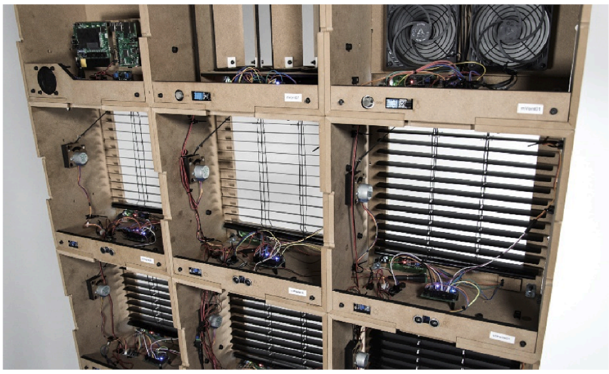


Figure 9. (Video1) Back side of the prototype with visible technical components.

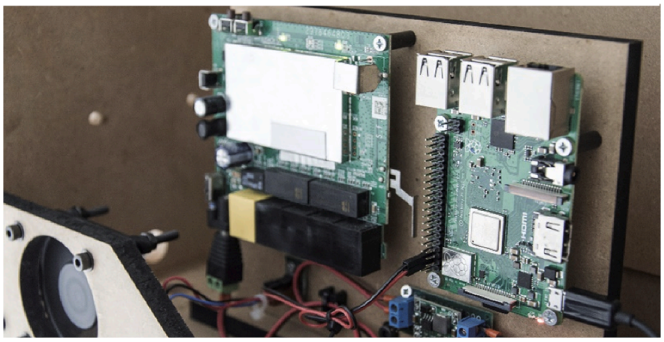


Fig. 10. Detail of the integrated router on the left and the Raspberry Pi server on the right.

ble connection to a digital twin, which reflects the configuration and adaptations of the physical system.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jobe.2020.101397

3.4. Test 4 - Shared sensor information

The fourth test demonstrates the possible cross-functional exchange of sensor information. In the example examined here, the sun protection is in a closed and lowered state as a reaction to direct sunlight. As soon as the upper sun protection module sShade02 detects a user via the integrated distance sensor as shown in (video5) Fig. 14, it opens the view to the outside by rotating the sun protection slats. The sShade05 sun protection component located below does not have an integrated distance sensor but receives the sensor information from the sShade02 module and also reacts by opening the slats. As soon as a user is no longer recognised, the upper module also shares this information and both functions return to their original configuration. The shown exchange of sensor data represents a possible form of cooperation between the modules as formulated in the fourth research question.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jobe.2020.101397

3.5. Test 5 - Collaborative decisions

The communication between the individual modules enables joint decisions with regard to the fourth research question regarding a possible cooperation, as well. As an exemplary scenario, the total of six sun protection modules are exposed to direct sunlight. Covering the light sensor of one module as shown in (video6) Fig. 15 causes a deviation. On the cloud-based control level, the states of all sun protection modules are compared, and the deviation is detected. Contrary to its own sensor information that there is no need for sun shading, the module takes over the reaction of the majority in the system and closes the blinds. As can also be seen in the video, this occurs after a deliberately integrated waiting time, which prevents the blinds from continuously moving back and forth. As a result, the test shows the possible coordination between adaptations of different functions on the superordinate control level as another form of their interaction.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jobe.2020.101397

4. Discussion

In view of the demonstrated cooperation in the five conducted tests, the implementation of the prototype can be regarded as successful. However, it becomes clear that this is only a first approximation to the implementation of façades as cyber-physical systems. The investigation does not yet cover the technically correct façade structure, nor the constructive integration of required hardware into façade components and products. Other system architectures and network topologies are conceivable, and the prototype does not provide any measured information about the actual performance of a façade implemented as cyber-physical system.

Nevertheless, the prototype illustrates promising possibilities for the operation of automated-adaptive façades that result from a cyber-physical implementation. This includes the comprehensive collection of sensor data and their exchange and negotiation in the overall system. In addition to an increased reliability and measuring accuracy through redundantly integrated sensor technology emerges a detailed picture of the buildings environmental conditions prevailing in the exterior and interior as the basis for negotiated decisions of the system. According to the role model of industrial production as described in the introduction, a high flexibility becomes clear, which arises from the organisation of independently operating and communicating façade modules as agents of the system. They pursue individual interests that can be negotiated with each other via the higher level of control and can also be overwritten. The verified connection to a digital twin, which illustrates the close integration of the physical and cyber

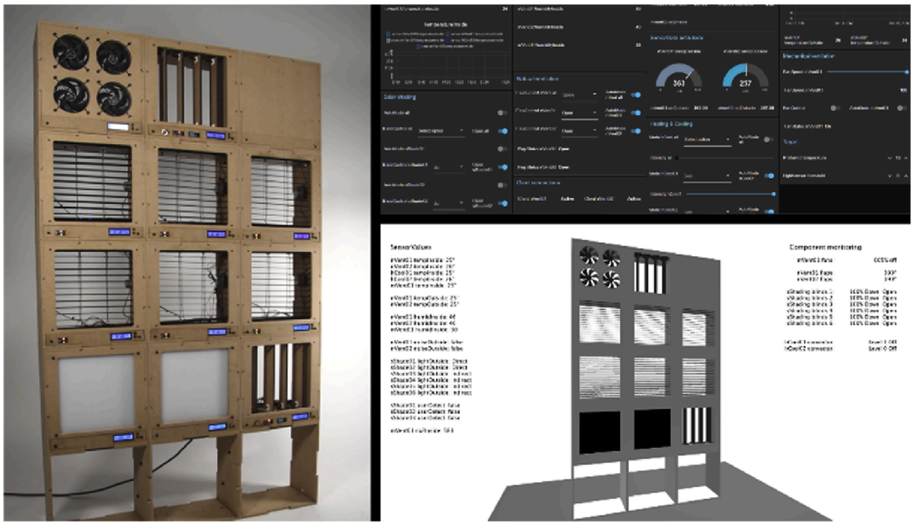


Figure 11. (Video2) Documentation of test 1.

Figure 12. (Video3) The ventilation flaps close due to noise pollution and mechanical ventilation is activated.

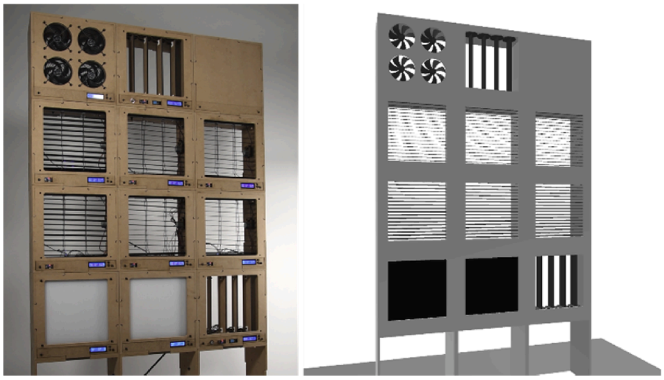


Figure 13. (Video4) Combined adaptations.

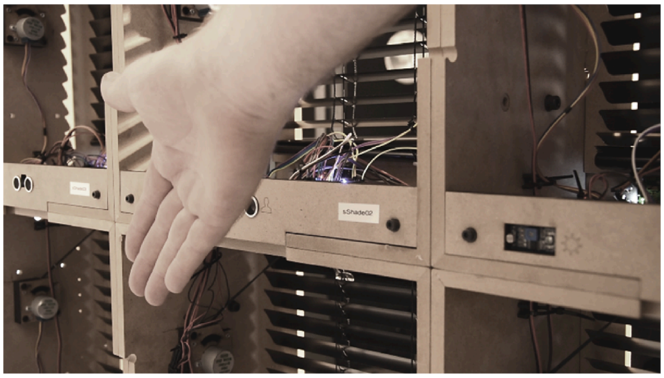


Figure 14. (Video5) Shared sensor information.

Figure 15. (Video6) Joint decisions between the modules.

levels and monitors the adjustment processes carried out, is also emphasized in this context. In line with the digital twins used in the industry, a future optimisation of the system via digital simulation of physical processes is also conceivable.

The distinction in the arrangement of inside and outside sensors in this study is to be understood as symbolic. Since the examination of the functionality is carried out in an indoor environment, identical conditions are measured by all sensors. The consideration of different measured data of the exterior and interior, which was established in the prototype, is therefore deliberately neglected in the tests of this study. Additionally, not all sensors installed in the prototype provide plausible data. This is partly due to the use of low-cost components and partly due to missing calibration, as in the example of the MQ2 and MQ135 gas sensors used. Since the focus of this work is on the fundamental functioning of the overall system, the reasonability of individual sensor data has not been further investigated.

The wired power supply used in the prototype raises the question of whether wireless communication in the façade is even desirable. In contrast to cyber-physical mobile systems such as moving robots or autonomous vehicles, the building and the arrangement of components are static. It is therefore also conceivable to network the components by cable, which is, according to Yang and Chen [30], generally less susceptible to faults. Wireless communication, on the other hand, is more flexible and promotes the scalability of the cyber-physical system as described by Hu et al. [31]. A potential is therefore seen in the interchangeability and expandability of the façade modules in the concept of a plug-play system described in the multi-functional plug and play façade project [32]. The greatest possible flexibility in the configuration of the physical system could then be achieved with a self-sufficient, module-integrated power supply, for example via photovoltaics.

5. Conclusion

After the evaluation, the research questions of the study can be answered as follows: With respect to the main question, important criteria of a cyber-physical system have been successfully implemented in the development of the façade prototype. The result shows only one possible structure of a cyber-physical façade, from which however relevant aspects can be derived. Because of the close integration of both domains, the first sub-question regarding the organisation of the system needs to be answered on the physical as well as on the cyber level. On the physical level, in particular the combination of durable building materials and high-tech electronic components requires a correspondingly modular and reversible design of the façade system as described in section 2.3. On the cyber level, the key to decentrally organized façade functions lies in the separation of their local and cloud-based control, as well as in the implementation of a communication system on the basis of which the individual functions can cooperate. As answers to sub-questions 2 and 3, the embedding of the façade functions is possible due a module-integrated micro controller, as is the respective installation of sensors and actuators. The communication between the modules was successfully implemented as an answer to sub-question 4 with the Machine-2-Machine communication protocol MQTT, which transports all relevant information as topic-related messages. With respect to research question 5, all carried out tests show that the façade functions can adapt locally in real time to changing sensor information. However, a delay in the range of milliseconds was observed during communication between the modules. The implementation of a digital twin as formulated in the fifth research question is possible and was implemented in the investigation due to missing software solutions, by means of a self-written program in the processing programming environment.

6. Future research

The study shows the general potential in the implementation of façades as cyber-physical systems and provides a first concept for the design. On the way to an actual applicability in building practice, however, there are still many future research tasks: These include the transformation described in the discussion into a real façade construction using appropriate building materials, products and automation technologies. In addition, project-specific relationships between the cyber-physical façade functions must be taken into account and integrated into the control concept. The superposition matrix by Böke [22] is identified here as a possible tool for the development of corresponding goal-oriented automation concepts. Furthermore, an energetic investigation of the actual performance of such a system is still pending.

During the development of the system it was noticed that there are no planning tools for the conception of adaptation strategies or cyber-physical building constructions. In addition to the physical components of the construction, these should also be able to map changeable configuration states, the communication and the behaviour of the system. The development of new software solutions or the connection to existing tools such as Grasshopper 3D or Revit-Dynamo seems to make sense to map automation decisions early in the planning phase and to close the gap to architects and designers. Software solutions for the implementation of digital twins exist in Industry 4.0, but have not yet been transferred to the construction sector. A further demand for research therefore lies in the realisation of building-related digital twins.

The presented prototype operates on a local wireless network. The connection to Internet-based services promises additional possibilities, for example through access to weather forecasts or any other relevant and available data. In this context security is an important topic [33]. The digital networking in the façade and its possible connection to the Internet represents a potential security risk against cyber-attacks. Granzer et al. [34] Further investigations are needed here, aiming at the protection of the façade system. In the network topology of the prototype, also the broker is regarded as a weak point. The entire communication runs through it. If the broker fails, the communication breaks down and the functions fall back on their internal feedback loops. In future investigations of the façade as a CPS, a decentralized structure of the communication also is desirable. The implementation as a mesh network described by Yu et al. [35] or the proposal of distributed brokers by Kawaguchi and Bandai [36] appears reasonable here.

A potential for further optimisation is especially seen on the cyber level, since the here performed decision processes determine the efficiency of the overall system. The presented system architecture in this study can be used as a framework for further investigation of applicable strategies of artificial intelligence or machine learning on cyber-physical façades to improve the goal-oriented behaviour of such systems.

CRediT authorship contribution statement

Jens Böke: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Visualization, Project administration. **Ulrich Knaack:** Conceptualization, Supervision. **Marco Hemmerling:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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