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Automated adaptive façade functions in practice - Case studies on office buildings

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ABSTRACT

The study examines the existing technical basis in building practice for the application of cyber-physical systems on the façade. The associated intelligent cooperation of automated adaptive façade functions, inspired by intelligent technical systems in industry 4.0, offers a potential for the overall building performance. By the type and scope of automations already introduced today, façade functions are identified that offer special potential for consideration in a cyber-physically implemented façade. The investigation represents a multiple case study analysis in which office façades in Germany are examined. Data is collected from literature, expert interviews and field investigations. The evaluation is carried out in a single case analysis and a following cross-case analysis, in which patterns and dependencies in the joint implementation of automated and adaptive façade functions are identified. The study found that especially sun-related functions are implemented adaptively, often in combination with ventilation and the heating and cooling support function.

1. Introduction

1.1. Background

Automation plays an important role in today's building projects. Building automation systems (BAS) control and monitor many aspects of building services to ensure the interior comfort while saving energy [2]. Building automation is organised hierarchically. Kastner, et al. [3] illustrate the structure of BAS in a three-level automation pyramid. At the lower field level, the system interacts with the physical environment via sensors and actuators. At the higher automation level, the information is processed, relationships are formed, and control loops are executed. The top level contains the management. This level represents the overall system and enables human intervention in addition to error alarming, archiving and trending. Building automation can be realized on different platforms. These include, for example, the international BAS standards: Lon, KNX or BacNet.

The façade is a central element of a building's climate and energy concept. It is located between the dynamic external boundary conditions and the interior comfort requirements of a building. In building operation, the parameters of both are constantly changing. The ability of the façade to adapt to changing conditions and requirements contributes to the efficiency of a building. Against this background, adaptive façades are intensively researched today [4]. The façade function tree developed by Klein [5] shows that the façade fulfils a multitude of different functions. Façades consist of different layers or components that fulfil these individual functions. Façades consist of different layers or components that fulfil these individual functions. Adaptations can be carried out by the intrinsic properties of smart materials as formulated by Lignarolo, et al. [6], or on the basis of automations. In this context automation technologies are already applied to façades. Many components fulfilling the façade functions meet the criteria of a mechatronic system due to the possible integration of sensors, existing processing systems in the form of a central control or embedded Micro-controllers, as well as possibly integrated actuators that perform physical adjustments of the construction [7,8]. The scope of introduced automation technologies depends on the respective project. The extent to which façades are automated also increases over the course of the integration of building services into the façade.

The technical possibilities in the field of automation technologies are multiplied today by the downscaling of electronic components, embedded software, and the possibility of comprehensive networking in the sense of an Internet of Things [9]. Cyber-physical systems refer to the close integration of automated physical applications with a networked digital control system. Such systems are applied in many areas and enable recent innovations such as autonomous driving, decentralised energy supply or robot-based surgery [10,11]. One field of application are intelligent technical systems in the manufacturing

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industry. The application of artificial intelligence to mechatronic production plants and the networking of individual machines toward intelligent technical systems are currently leading to a new stage of development, the so-called Industry 4.0. The objective of this cooperation of individual autonomous production facilities with regard to a common production goal is the increase of productivity and a greater flexibility within the production processes [12].

The current development of intelligent technical systems in the manufacturing industry is based on the existing infrastructure of a former mechatronic industrial production [13]. Contrary to the hierarchical structure of mechatronic systems, intelligent technical systems are organised decentrally. An essential aspect of such systems is the communication between machines and their interaction with humans. Monostori, et al. [14] formulate the ability to act on the basis of gathered information, the ability to connect to other components of the system, and the ability to respond to internal or external system changes as three essential characteristics.

Due to the automation technologies already applied to the façade, its implementation as an intelligent technical system based on the industrial role model is conceivable. Böke, et al. [15] provide the state of the art of intelligent façades in comparison to intelligent technical systems in the development of an industry 4.0. They formulate the possible transferability of the networking strategy described above to the automated, adaptive functions of the façade. In line with the objectives of the manufacturing industry, the cooperation of individual façade functions in an intelligent overall system should increase the efficiency and flexibility of adaptive façades in building operation. Böke, et al. [1] identify façade functions, which can theoretically become part of such an intelligent technical façade system due to a possible adaptive implementation and an effect on the building performance. With a superposition matrix, they provide a tool for assessing the automated adaptive implementation of individual façade functions on the basis of predefined characteristics.

1.2. Problem statement

The application of cyber-physical systems to automated adaptive façade functions in the operating phase of the building has neither been investigated nor verified. According to the model of application in intelligent technical systems in the Industry 4.0, an expected technical requirement lies in an existing infrastructure of automation technologies. The actual conditions in practice are unclear. Detailed information is lacking about which façade functions become implemented at all and to what extent they are realized in an automated, adaptive manner in order to represent a potential part of a cyber-physical façade system. For a following investigation of the potential of such a system, no functions can yet be excluded because of a never implemented automated adaptivity. Knowledge is also missing about which automated and adaptive functions are implemented together and are therefore of particular interest for concepts of intelligent cooperation in the sense of a cyber-physical system.

1.3. Objectives and research questions

The aim of the investigation is to clarify the actual conditions in the automation of façades in construction practice. Potential façade functions are to be identified as promising units in the development of cyber-physical façades. For this purpose, functions are to be determined, which become implemented automated and adaptive in practice. Also such functions are to be identified which have a low priority for consideration because they never become implemented automated adaptive. A further objective is the recognition of recurring patterns in the selection and implementation scope of automated adaptive façade functions.

The study is subject to the main question: How and to what extent is automation applied to façades and which façade functions are taken into account? The research question is divided into the three subquestions:

- Which automated-adaptive façade functions are implemented in practice?
- Which facade functions are not automated adaptive or not implemented at all?
- Can priorities and patterns be derived in the selection and scope of automated adaptive facade functions?

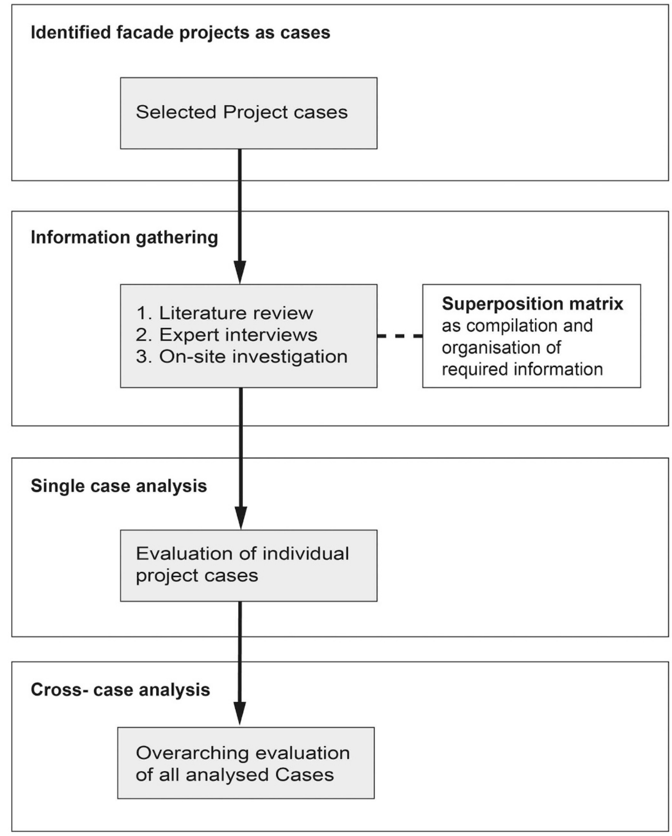

Fig. 1. Methodology diagram.

2. Methodology

The study presents a multiple case study analysis. Inspired by the case study of intelligent façades conducted by Wigginton and Harris [16], it examines a total of eleven realized façade projects with regard to automated adaptivity. As shown in the methodology diagram in Fig. 1, a superposition matrix developed by Böke, et al. [1] serves as the organisational structure for the survey. It combines possible adaptive and performance-relevant façade functions with characteristics of an adaptive implementation. The matrix is applied to the selected façade projects and allows the systematic examination of the different cases. Each examined building envelope project represents one case in the sense of this study.

2.1. Selection of projects

The projects are identified in two stages. In an initial search, a set of 45 projects is identified via internet portals and certification databases. The selection is based on the following criteria: due to the accessibility and the experience of the Central European climatic conditions and requirements for buildings, the geographical focus of the investigation lies on Germany. The investigation is limited to the typology of office buildings, since the requirements for workplaces are comprehensively defined and documented by German regulations. The technological basis in the area of automation technology has only been established during the past decades. As a result, only recent projects are considered for the investigation, projects which were realized in the year 2000 at the earliest. In addition, the study is based on the assumption that comprehensive automation technology is used from a specific project size onward. Therefore, the investigation focuses on large projects. The final selection contains eleven projects that are examined in this case study analysis. The selected number of investigated projects was decided on the basis of the highest possible informative value with a feasible workload within the study. Another criterion for the selection of the projects was the accessibility of project information and data.

2.2. Collection of data

The study follows the principles of data collection formulated by Yin [17] and takes place in a mixed-methods approach using literature reviews, expert interviews and field investigations. The data is successively recorded in the superposition matrix developed by Böke et al.

2.2.1. Literature review

The literature search is carried out for each of the examined projects. The aim is to determine background knowledge on the corresponding façade project. Data that can already be obtained from the literature is included in the data set of this study. In addition to information on the context of the building and the general construction of the façade, the literature is also used to identify contact persons for the expert interviews. The background knowledge of the projects serves as a basis for conducting these interviews.

2.2.2. Expert interviews

The interviews are structured and based on a previously developed interview guide. It is hierarchically organised and comprises, at a minimum, the query of automation-relevant project information and fulfilled façade functions in 18 questions. If a fulfilled function is identified, detailed questions may follow, questioning its particular implementation. The interview guide predominantly consists of closed questions, which can be answered with yes or no. For some of the questions the answer is part of a range of possibilities. Most of the surveyed experts are people with responsibility and deadline pressure in current construction projects. Against this background, a written survey was not considered a very promising path, and the decision was made to conduct verbal interviews despite the high proportion of closed questions.

The interview guide is organised in two categories. In the first category, the basic requirements of the façade as a complete system, such as the general application of automation technologies and the technological platform for their implementation, are clarified. It is also investigated whether coordination between the automated-adaptive façade functions takes place and if the automation control is centrally or decentrally organised. In the second part of the interview guide, the adaptive features of specific façade functions are examined. The selection of functions and the questions regarding their adaptive implementation are derived as illustrated in Fig. 2 from the Superposition Matrix developed by Böke, et al. [1]. In addition to elementary façade tasks, such as thermal insulation or sun protection, it also covers functions that can be optionally integrated depending on the project requirements. For example, the generation of energy or the integration of supply functions. Therefore, the first question is whether a particular façade function is fulfilled in the project at all. If this is the case, the corresponding technology or component is clarified and detailed questions about its actual implementation follow. According to Böke, et al. [1], a distinction is made in this study between a façade function classified as flexible, whose configuration can be changed only manually by the user, and an adaptive façade function, which adapts independently due to its automated control. To determine if a function is implemented as a flexible system, the interviewee is asked whether its configuration can be changed or not. The answer to the question of whether the component adapts itself or requires a user impulse decides

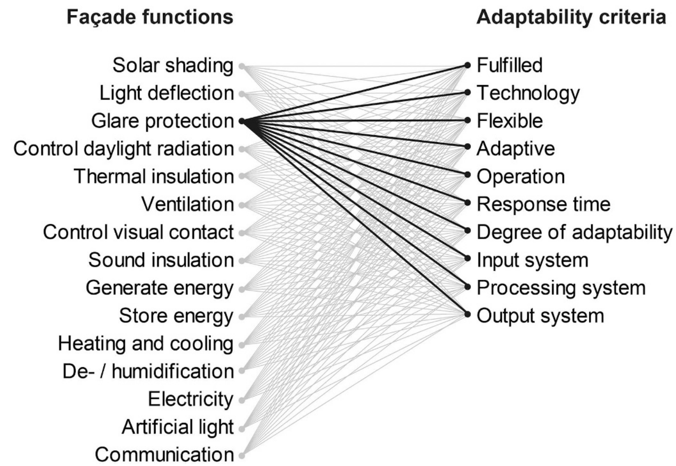

Fig. 2. Basic structure of the superposition matrix by Böke, et al. [1].

whether the façade function is considered as adaptively implemented. Three separate questions examine whether sensors, control technologies and actuators are used in the functionality of a component. If this is the case, the façade function fulfils the technical requirements of a mechatronic system. Loonen, et al. [18] distinguish between the extrinsic and intrinsic operation of an adaptive façade. Within automated, extrinsically operated adaptive façades, a control pulse is required to initiate adjustments, while the adaptation is inherent in an intrinsic system corresponding to smart materials. An extrinsic operation of a façade function is recorded if its comprehensive adaptivity is determined by the characteristics of a mechatronic system. The degree of adaptability is clarified by asking whether the component can be adapted in on-off states or gradually. The question of the time intervals at which adjustments to the façade function are carried out relates to its response time. Table 1 shows the actual formulation of the function related questions and the assignment of corresponding answers.

According to Bogner, et al. [19], experts are people who have relevant knowledge on a specific subject area and practical relevance in this field. Following this assessment, in this study persons are regarded as experts who have knowledge of the concrete technical implementation of the investigated façade project due to their project participation. In addition to architects and engineers, this can also include specialist planners and representatives of the construction companies carrying out the work. The interviews are conducted either in person or by telephone. Answers are recorded in writing during the conversation. It is possible that the interviewed expert cannot answer certain questions. This case is marked with an entry in the protocol as not available (NA). After conducting the interviews, the protocol is sent to the respective interview partners for verification and possible correction. Due to the common national language, the interviews are conducted in German and then translated.

2.2.3. Field investigation

The projects examined are personally visited as part of the field investigation. The aim is to supplement and review the data already collected from literature and the interviews. Not all aspects of the technical implementation can be examined by personal assessment. Due to the buildings' commercial use and existing company safety regulations, often inspection of the façade is limited to the outside. Technical details of the control system are beyond this consideration. However, conclusions can be drawn about the façade's automated implementation from different states of its components. For example, whether the sun protection is set identically or differently for all rooms. The personal investigation contributes to the understanding of the questioned construction and the automated façade functions implemented therein. The examined buildings and the configuration of their façades are documented by photos during the on-site investigation.

Table 1
List of interview questions per function.

Question	Answer	Assignment
Is the façade function fulfilled in the façade construction?	Yes/no	Fulfilled
Which component or construction element fulfils this façade function?	Element	Technology
Can its configuration be changed within the buildings use phase? (Open/closed)	Yes/no	Flexible
Does the component or construction element enable on-off or gradual states?	Yes/no	Degree of adaptability
Is the component or construction element able to adapt itself or is a user impulse required?	Yes/no	Adaptive
Are sensors connected to the function of the component?	Yes/no	Input system
Does the component have actuators?	Yes/no	Output system
Does the component have an embedded control?	Yes/no	Processing system
In what temporal intervals do adjustments take place?	Interval	Response time
Is the adjustment carried out by a smart material?	Intrinsic	Operation

Table 2
Protocol of research investigations.

#	Project	Interview partner	Affiliation	Background	Date of interview	Field investigation
1	Triangle cologne	Möllering, Christian	Enervision GmbH	System integrator	23 July 2018	06 February 2018
2	Q1 Thyssen Krupp Headquarter	Möllering, Christian	Enervision GmbH	System integrator	23 July 2018	02 July 2018
3	Oval Offices	Möllering, Christian	Enervision GmbH	System integrator	23 July 2018	05 February 2019
4	Z_Zwo	Becker, Eike	Eike Becker_Architekten	Architect	31 June 2018	08 February 2019
5	KFW Westarkade	Auer, Thomas	Transsolar	Energy consultant	02 October 2018	06 February 2018
6	Post tower	Cook, Steven	Jahn	Architect	22 October 2018	03 February 2019
7	Kap am Südkai	Zimmermann, Michael	Michael Zimmermann & Co. GmbH	Architect	26 November 2018	16 February 2018
8	HDI Gerling Headquarters	Bruder, Barbara	Ingenhoven architects	Architect	11 December 2018	15 February 2019
9	Horizon L'Oréal Headquarters	Heimann, Stephan	HPP Architekten GmbH	Architect	31 August 2018	23 February 2019
10	Vodafone Campus	Heimann, Stephan	HPP Architekten GmbH	Architect	31 August 2018	23 February 2019
11	Capricorn house	Gaessler, Sven	GATERMANN + SCHOSSIG Architekten GmbH	Architect	28 January 2018	02 July 2018

2.2.4. Protocol

Table 2 documents the investigations carried out on the respective projects. The names of the contact persons and their affiliations as well as the dates of the interviews and on-site investigations are listed.

2.3. Analysis and interpretation of data

Each project is first evaluated as a single case. For this purpose, the project-related findings are consolidated and transferred to the superimposition matrix [17]. Different instruments were chosen for the presentation of the information obtained. This includes reference images from the photo-based documentation of the project's field investigation. A brief project description clarifies the project context and general aspects of the building energy concept. The description also includes details on the project's façade automation that exceed the questions posed by the interview guide. The data collected from the interviews is presented in diagrams that enable a quick and comparable consideration of the individual projects. Abbreviations and symbols are used in these charts. Their meaning is explained in the legend presented in Table 3.

The single case evaluation is followed by a cross-case analysis of all investigated projects. According to Stake [20], the focus lies on recognizing similarities and differences between the cases. Data visualizations are used to recognize patterns in the joint implementation of automated and adaptive façade functions according to the third research question. Therefore, the information from each single case analysis is consolidated in a comprehensive data set and evaluated according to frequencies. Different forms of data visualization are applied. Frequencies in the implementation of fulfilled, flexible and adaptive façade functions are visualized in a stacked bar graph. Due to their focus on connections, non-ribbon chord diagrams are used to highlight focal points in the joint implementation of façade functions. Proportions of projects classified as centrally or de-centrally controlled are represented in a pie chart.

2.4. Obstacles and limitations

One uncertainty lies in the overlapping of different functions. For example, if one component covers several functions, or if a façade function is fulfilled by the interaction of several components. In case of doubt, the component essential for the function is recorded and the overlap is noted in the protocol. Another risk lies in different possible interpretations of when a function is considered fulfilled. For example, if it is not intentionally introduced but mechanisms of other functions affect it. Opening and closing windows, for example, naturally has an effect on the sound insulation of the building, even if the process is not primarily concerned with fulfilling this function. With regard to these uncertainties, the decision processes are noted in the project descriptions and protocols.

3. Results

3.1. Single case analysis

In this section, the results of the eleven selected projects are examined individually. In addition to a project description with illustration, each project evaluation on the basis of the superposition matrix is presented as a diagram.

3.1.1. Case triangle Cologne

Architects Gatermann + Schossig designed the high-rise building, completed 2007 in Cologne. The building consists of the tower building

Table 3
Legend for the single project chart.

●	Yes	**E**	Extrinsic	**G**	Gradual	**S**	Seconds	**H**	Hours	**M**	Months	**NA**	Not available
○	No	**I**	Intrinsic	**X**	On-Off	**Min**	Minutes	**D**	Days	**A**	Years		

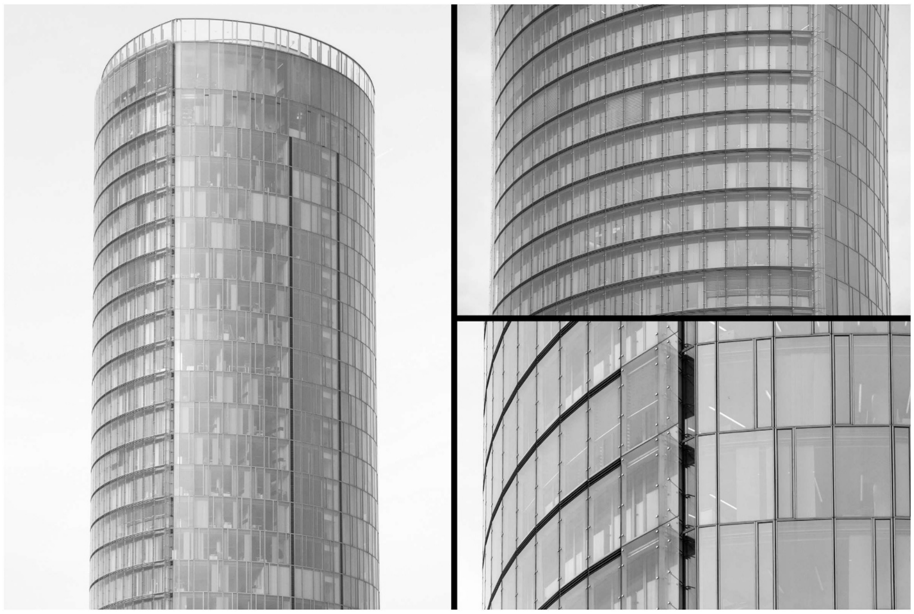

Fig. 3. Triangle building in Cologne.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Lamella in double facade	●	●	E	Min	G	●	●	●
Light deflection	○									
Glare protection	●	Lamella in double facade	●	●	E	Min	G	●	●	●
Control daylight radiation	●	Lamella in double facade	●	○	E	Min	G	●	●	●
Thermal insulation	●	Double facade	○							
Ventilation	●	Double facade & Windows	●	○						
Control visual contact	●	Lamella in double facade	●	○	E	Min	G	●	●	●
Sound insulation	●	Double facade	○							
Generate energy	○									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 4. Evaluation of the Triangle Tower.

and a pedestal building. It comprises office spaces and a conference centre. The top floor is available to the public as a viewing platform [21]. Fig. 3 shows that the façade consists of two sections. On one half, it is implemented as a single skin, on the opposite half it is extended by an additional layer to form a double façade. The construction is equipped with automation technologies. Its control is based on the "RaumComputer" platform and involves decentralised operation of the components, which are centrally parameterized. A visual feature is internal louvres, which guarantee the sun and glare protection of the building. The louvers are opened and closed automatically in minute intervals and with regard to the fulfilment of these two functions. The user can override the control and adjust the louvers as desired to control the incidence of daylight or the visual contact to the outside. Since user intervention is required here, both functions are not considered to be adaptive, even if they contain the corresponding features of an automated implementation. Ventilation is provided by windows that can be opened manually. The double façade structurally fulfils the functions of sound- and thermal insulation. Fig. 4 shows the detailed evaluation of the project based on the expert interview [22] (C. Moellering, personal communication, July 23, 2018).

3.1.2. Case Q1 Thyssen Krupp Headquarter

The administrative building Q1 of the German company ThyssenKrupp was completed in 2010 in Essen. JSWD architects designed this central part of the ThyssenKrupp quarters, which comprises 9 additional buildings. The concept of the façade is based on two design principles. Toward the outside, it is to limit the building as a "shell". Inside, it opens to the atriums and courtyards, according to the concept of a "core". Automation technologies are used in the building envelope. The façade construction consists of a metal-glass layer that is supplemented by external and vertically oriented metal louvres which provide sun and glare protection. As Fig. 5 shows, they determine the appearance of the building. With their possible rotation, regulated by 1280 engines they are identified in Fig. 6 as the only adaptive components of the project [22]. Four elements are controlled together as one unit. The user can override the automated control of the louvres, for example, to change the external view relationships. The façade automation is based on the LON platform and the parameters of the decentralised control

Fig. 5. Q1 Thyssen Krupp Headquarter.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Vertical lamella	●	●	E	Min	G	●	●	●
Light deflection	○									
Glare protection	●	Vertical lamella	●	●	E	Min	G	●	●	●
Control daylight radiation	○									
Thermal insulation	●	Facade	○							
Ventilation	○									
Control visual contact	●	Vertical lamella	●	○	E	Min	G	●	●	●
Sound insulation	●	Facade	○							
Generate energy	NA									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 6. Evaluation of Q1 ThyssenKrupp.

are configured centrally [22] (C. Moellering, personal communication, July 23, 2018).

3.1.3. Case oval offices

The project consists of two similar office buildings designed by Sauerbruch Hutton. They were completed in 2000 in Cologne at the banks of the Rhine river. An important aspect of the building's energy concept is its heating and cooling system. It uses water from the adjacent Rhine via a heat exchanger and floor integrated pipe system. The fully glazed façade consists of storey-high windows and double-glazed panels. High glass shutters are installed in front of it, which serve as sun protection and determine the appearance of the building with their colour scheme [23]. The shutters shown in Fig. 7 are flexible and can be opened and closed independently. The automation of the façade is based on Zumtobel Luxmate and on Schneider TAC, which is a LON-based automation platform. The parameterization of the decentralised control concept takes place centrally. The automated façade functions are not coordinated with each other. The control system is organised in sections, and not embedded in the shutters. Following Moellering, it still presents a highly decentralised system. The opening and closing of the shutters can be manually overridden for each room. The building envelope fulfils the functions of sound and thermal insulation in a static implementation. As Fig. 8 shows, only the functions solar shading and glare protection are regarded as adaptive, because of a necessary user impulse to control the visual contact and the ventilation [22] (C. Moellering, personal communication, July 23, 2018).

3.1.4. Case Z_Zwo

Eike Becker architects designed the office building "Z_Zwo" for Züblin Projektentwicklung GmbH and completed it in 2002 in Stuttgart-Möhringen. As visible in Fig. 9, the building is characterised by an organic wave shape. One feature is the massive balustrades, which, as part of the energy concept, reduce the glass content for lower summer heat gains. The façade presents a highly thermally insulated construction with about 80% window area. The automation technology integrated into the façade is controlled centrally. External aluminium blinds driven by an electric motor provide sun protection and light deflection. The blinds consist of an upper area with horizontally

Fig. 7. Oval offices in Cologne.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Shutters	●	●	E	Min	G	●	●	●
Light deflection	○									
Glare protection	●	Shutters	●	●	E	Min	G	●	●	●
Control daylight radiation	○									
Thermal insulation	●	Facade	○							
Ventilation	●	Windows	●	○						
Control visual contact	●	Shutters	●	○	E	Min	G	●	●	●
Sound insulation	●	Facade / Shutters	○							
Generate energy	○									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 8. Evaluation of Oval Offices Cologne.

positioned blades that direct light into the interior, and a lower section that protects against the sun. In addition to raising and lowering the blinds, their angle changes depending on the outside temperature and light incidence. A digital control system manages the sun protection and the opening of the windows with the aim of optimising the building's energy consumption. Fans are installed in the roof area to create a low pressure on the inside. In combination with openable windows, they enable night purge ventilation. The openable windows are designed to be soundproof to protect against external noise. This aspect is not part of the automated control. However, the windows, as the essential components for this function, have integrated automation technology. Accordingly, in the evaluation in Fig. 10 they are regarded as flexible and automated, but not as adaptive due to the lack of independent adaptation with regard to sound insulation. The user can open or close the blinds and windows individually via switches in the windowsill. In the event of high wind loads, a sensor triggers the system's safety mechanism and ensures that the external blinds are raised [25] (E. Becker, personal communication, June 31, 2018) [24].

3.1.5. Case KFW Westarkade

Sauerbruch Hutton designed the main building of the KFW bank and completed it in 2010. It is a 60 m high-rise building on a pedestal building [25]. The double façade of the building consists of flared elements and coloured motor-driven ventilation flaps. Ventilation is an important aspect of the overall building energy concept. In summer, the ventilating louvres allow the warm air to escape from the intermediate space. The opening of the flaps depends on the current temperature and wind speeds. In winter, closing the flaps allows pre-heating the air. The sun and glare protection is installed between the two façade layers. It is based on a central control system that can be overridden by the user. Fig. 11 shows that different gradual states are possible in the opening of the slats. With regard to controlling the visual relationship with the outside, the user must intervene in the automated control. The outer layer of the façade protects the building from wind loads, mainly occurring at the building's upper part. Both, the building and the façade are shaped with respect to the wind direction. The stepped geometric structure and the double-cladding of the façade affect the interior

Fig. 9. Projct *Z*-Zwo.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	External jalousie	●	●	E	NA	G	●	●	●
Light deflection	●	External jalousie	●	●	E	NA	G	●	●	●
Glare protection	●	External jalousie	●	●	E	NA	G	●	●	●
Control daylight radiation	●	External jalousie	●	●	E	NA	G	●	●	●
Thermal insulation	●	Glass facade	○							
Ventilation	●	Windows + ventilators	●	●	E	D/M	G	●	●	●
Control visual contact	●	Windows & External jalousie	●	○	E	NA	G	●	●	●
Sound insulation	●	Facade & Windows	●	○	E	NA	G	●	●	●
Generate energy	○									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 10. Evaluation of the Project Z-ZWO in Stuttgart.

acoustics. The sound insulation is supplemented by absorber surfaces integrated into the intermediate space of the façade. Pre-installations are integrated into the façade elements, such as sensors and motors to control the ventilation flaps or empty conduit for laying electrical cables [26,27]. Fig. 12 shows the detailed evaluation of the project on the basis of the interview with Auer [30] (T. Auer, personal communication, October 02, 2018).

3.1.6. *Case post tower*

The Post Tower office building was completed in 2003 for Deutsche Post AG in Bonn. Murphy & Jahn architects designed the elliptical high-rise. The façade is a completely glazed double-shell construction. The outer layer protects against external weather conditions such as wind and rain. It rises above the actual building and encloses a roof garden as well as penthouse offices on the upper floors. The inner layer is insulation-glazed and transparent. Automation technology is used in the façade and according to Blaser [28], it is adaptable and switchable. The automation concept is based on a centralized control system. It regulates the natural ventilation of the offices and the daylight entering the rooms. As visible in the evaluation in Fig. 14, the façade also fulfils supply functions such as heating, cooling, humidification and dehumidification. Convectors are integrated into the floors of the building,

Fig. 11. KFW Westarkade in Frankfurt.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Sun shading lamellas	●	●	E	H	G	●	●	●
Light deflection	○									
Glare protection	●	Sun shading lamellas	●	●	E	H	G	●	●	●
Control daylight radiation	●	Sun shading lamellas	●	●	E	H	G	●	●	●
Thermal insulation	●	Double facade	●	●	E	H	G	●	●	●
Ventilation	●	Ventilation flaps and windows	●	●	E	H	G	●	●	●
Control visual contact	●	Sun shading lamellas	●	○	E	H	G	●	●	●
Sound insulation	●	Absorber in double facade	○							
Generate energy	○									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 12. Evaluation of the KFW Westarkade.

which heat and cool the air from the space between the façade, depending on the winter- or summer season. The sun and glare protection is provided by automated louvres located between the two shells. The intermediate space also houses the technology for the nocturnal light staging of the façade. Fig. 13 shows that, contrary to the north side, the façade elements on the south side are arranged imbricated for better air circulation [28]. The coordination of the façade-integrated ventilation flaps is also centrally controlled [32] (S. Cook, personal communication, October 22, 2018).

3.1.7. Case Kap am Südkai

The office building Kap am Südkai was designed by KSP Engel und Zimmermann and completed in 2004 at the Rheinauhafen in Cologne. It consists of a five-storey glazed building block and a ten-storey office tower [29,30]. The façade is partly a double façade construction. Natural ventilation is provided by windows with an additionally added baffle plate. The change between the single-leaf and double façade elements characterises the appearance of the building envelope as shown in Fig. 15. Automation technology is used in the building

Fig. 13. Post tower in Bonn.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Lamellas in double facade	●	●	E	S	G	●	●	●
Light deflection	○									
Glare protection	●	Lamellas in double facade	●	●	E	S	G	●	●	●
Control daylight radiation	○									
Thermal insulation	●	Double facade / Inner layer	○							
Ventilation	●	Windows + Convectors	●	●	E	NA	G	●	●	●
Control visual contact	●	Lamellas in double facade	●	○	E	NA	G	●	●	●
Sound insulation	●	Double facade	○							
Generate energy	○									
Store energy	○									
Heating and cooling	●		●	●	E	NA	NA	●	●	●
De- / humidification	●		●	●	E	NA	NA	●	●	●
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 14. Evaluation of the Post tower in Bonn.

envelope. The sun protection consists of room-high, automated louvres, which are installed partly on the outside, partly on the inside of the double façade construction behind the baffle plate. The control of the sun protection identified in Fig. 16 can be regulated room by room as well as individually. Each louvre has its own control panel, via which the user can intervene in the energetically motivated regulation of the sun protection. This also enables the individual control of visual relationships to the outside. This function is considered flexible and automated, but not adaptive due to the necessary user impulse. The glare protection was not part of the façade concept, it was partially retrofitted independently of the façade [32] (M. Zimmermann, personal communication, November 26, 2018) (Fig. 17).

Fig. 15. Kap am Südkai.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Sun shading lamellas	●	●	E	S	G	●	●	●
Light deflection	●	Sun shading lamellas	●	●	E	S	G	●	●	●
Glare protection	○									
Control daylight radiation	●	Sun shading lamellas	●	●	E	S	G	●	●	●
Thermal insulation	●	Double facade	○							
Ventilation	●	Window	●	○						
Control visual contact	●	Sun shading lamellas	●	○	E	S	G	●	●	●
Sound insulation	●	Front impact pane	○							
Generate energy	○									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 16. Evaluation of the building Kap am Südkai

3.1.8. *Case HDI Gerling Headquarters*

The headquarters of the HDI-Gerling Insurance Group is located in Hanover. The building, designed by Ingenhoven Architekten, was completed in 2011. It consists of a central, glazed atrium with adjacent U-shaped office bars. The atrium serves as a thermal buffer zone. Underneath lies a technical room with ventilation systems and heat exchangers. The ventilation system is used in the winter and summer months. Natural ventilation takes place during the transitional seasons. The building's energy concept uses geothermal energy and district heating. Daylight and presence sensors provide information for the control of the energy-optimised lighting of the building. The façade of the office buildings consists of a triple-glazed window band with parapet elements arranged underneath [31]. Fig. 18 shows the evaluation of the interview conducted with Bruder [37] (B. Bruder, personal communication, December 11, 2018) (Fig. 19).

Fig. 17. HDI Gerling Headquarters.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	External sun blinds	●	●	E	S	G	●	●	●
Light deflection	●	Light deflection lamellas	●	●	E	S	G	○	●	●
Glare protection	NA									
Control daylight radiation	●	External sun blinds	●	●	E	S	G	●	●	●
Thermal insulation	●	Triple glazing	○							
Ventilation	●	Windows (natural)	●	○			G			
Control visual contact	●	Parapet	○							
Sound insulation	●	Triple glazing	○							
Generate energy	○									
Store energy	○									
Heating and cooling	●	Heating/cooling pipe	●	●	E	NA	G	●	●	○
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 18. Evaluation of the HDI-Gerling Headquarter.

3.1.9. Case Horizon L'Oréal Headquarters

HPP Architects designed the Horizon L'Oréal Headquarters building in Düsseldorf and completed it in 2017. Offset storeys create balconies on the front sides of each level. Part of the building shell is designed as a double façade. Automation systems are used in the façade project and were implemented on the KNX platform. The sun shading is implemented differently, depending on the façade section. As also identified in the evaluation in Fig. 20, automated sun protection slats are installed in the space between the double façade. In the areas that are designed as single-layer façades, there is sun protection glazing with internal sun shading lamellas. There are also areas with fixed ceramic lamellas. For glare protection and the control of visual relationships, especially in sensitive areas such as the academy rooms, roller blinds are partly mounted on the inside, which can be adjusted manually by the user. The climatic conditioning of the rooms is carried out mechanically. In every 2nd façade element, there are additional openable rotary window elements installed, which the user can open and close manually up to a predefined limit. According to Heimann, these revolving windows are not necessary from a climatic point of view and are psychologically motivated to give the user the freedom to intervene in the configuration of the façade [38] (S. Heimann, personal communication, August 31, 2018).

Fig. 19. Horizon L'Oréal Headquarters.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Sun shading lamellas	●	●	E	S	G	●	●	●
Light deflection	●	Sun shading lamellas	●	●	E	S	G	●	●	●
Glare protection	●	Blinds	●	○						
Control daylight radiation	○									
Thermal insulation	●	Insulation glazing	○							
Ventilation	●	Window	●	○						
Control visual contact	●	Blinds	●	○						
Sound insulation	●	Glazing with foils	○							
Generate energy	○									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 20. Evaluation of Horizon Lóereal.

3.1.10. *Case Vodafone Campus*

The Vodafone Campus in Düsseldorf was completed in 2012. It was designed by HPP Architects and consists of an office tower with an attached building block [32]. According to Heimann and as illustrated in Fig. 22, automation systems are not applied in the façade project or are only used in a few minor sections, for example in individual blinds. The lower part of the façade consists of a mullion-transom system. In the upper area, it is realized as a closed element façade. As can be seen in Fig. 21, perforated white aluminium slats are mounted on the outside in front of the glass surfaces. They determine the external appearance of the façade and fulfil the sun shading of the building. The immovable design of the sun shading slats complies with the legal requirements of the Energy Saving Ordinance (ENEV) at the time the building was completed. The updated requirements of the current version, however, are not met in 2018 according to Heimann, S. The ventilation of the building is carried out mechanically and façade-independent. On all five axes, there are windows which the user can open and close manually. LED technology is integrated into parts of the façade. It is not

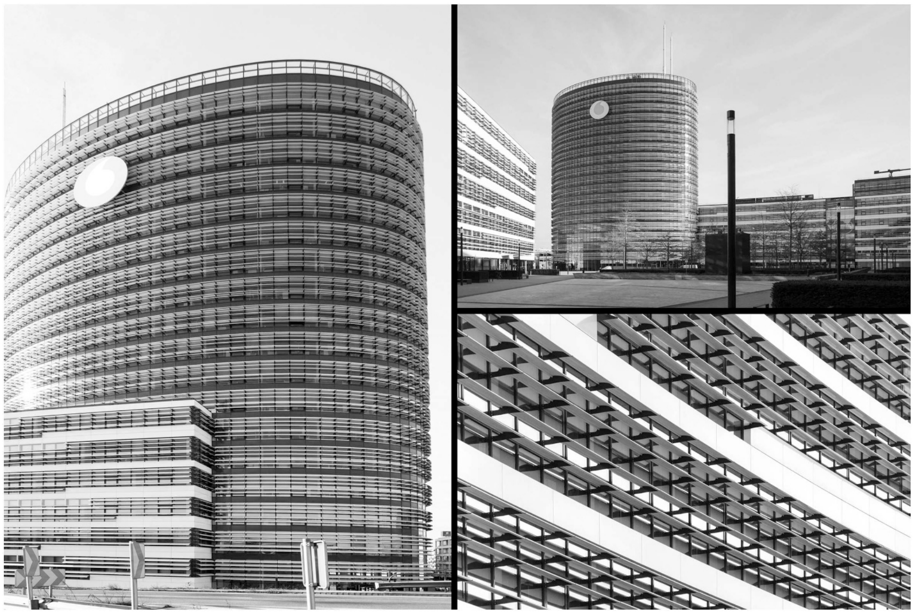

Fig. 21. Vodafone Campus.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Sunshading lamellas	○							
Light deflection	○									
Glare protection	●	Blinds	●	○						
Control daylight radiation	●		●	○						
Thermal insulation	●	Insulation glazing	○							
Ventilation	●	Window	●	○						
Control visual contact	●	Blinds	●	○						
Sound insulation	●	Insulation glazing	○							
Generate energy	○									
Store energy	○									
Heating and cooling	○									
De- / humidification	○									
Electricity	○									
Artificial light	○									
Communication	○									

Fig. 22. Evaluation of the Vodafone Campus.

used for lighting but for media projections on the building [38] (S. Heimann, personal communication, August 31, 2018) (Fig. 23).

3.1.11. Case Capricorn house

The Capricornhaus is located in Düsseldorf Medienhafen. It was planned by Gatermann Schossig architects and completed in 2008. The floor plan of the building results in four glazed atriums. They contribute to the building's climate concept by generating solar heat, which can be released through roof hatches in summer [33]. The entrance hall is located in the largest atrium. The façade is an element façade with the I-Module System developed by Gatermann Schossig. The name I-Module stands for integral and modular. The appearance of the façade is characterised by red glass panels [21]. Various climate functions such as cooling, heating and ventilation are integrated into the façade modules. Each façade module consists of a transparent and an opaque part. A box window with an insulated glass door behind it forms the transparent area. In the cavity between both layers are automated sun shading lamellas. There is also fixed glazing above the opaque elements. The opaque part is vacuum-insulated and houses the air-conditioning technology, which is integrated behind the non-transparent glass element. In addition to the transport of supply and exhaust air, the concept includes a fine dust filter and heat recovery, which can be bypassed by flaps if necessary. According to Knaack, et al. [34], the façade also performs artificial lighting functions. Façade lights are integrated into the modules for this purpose. Fig. 24 shows the evaluation of the project based on the interview conducted with [42] (S. Gaessler, personal communication, January 28, 2018).

Fig. 23. Capricorn house.

	Fulfilled	Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptability	Input system	Processing system	Output system
Solar shading	●	Sun shading lamellas	●	●	E	NA	G	●	●	●
Light deflection	●	Sun shading lamellas	●	●	E	NA	G	●	●	●
Glare protection	●	Sun shading lamellas	●	●	E	NA	G	●	●	●
Control daylight radiation	●	Sun shading lamellas	●	●	E	NA	G	●	●	●
Thermal insulation	●	Eement facade	○							
Ventilation	●	Window	●	○						
Control visual contact	●	Eement facade	●	○	E	NA	G	●	●	●
Sound insulation	●	Window	○							
Generate energy	○									
Store energy	○									
Heating and cooling	●	Parapet	●	●	E	NA	NA	●	●	●
De- / humidification	○									
Electricity	●									
Artificial light	●	Integrated lights	●	NA						
Communication	○									

Fig. 24. Evaluation of the Capricornhaus.

3.2. Cross case analysis

The cross case analysis combines the data of the individual case studies into a holistic view. Fig. 25 compares the frequencies of the fulfilled façade functions in the examined projects. The horizontal axis reflects the total number of eleven projects in which the respective function was found. The proportions of a flexible realisation, coloured in magenta, and an adaptive realisation, coloured in blue, are also taken into account. The comparison shows that core functions such as solar shading, thermal and sound insulation and also the control of visual contacts to the outside are fulfilled in all of the projects examined. The proportion of independent adaptability is highest in the area of sun-related façade functions, in particular, solar shading. The functions light deflection, glare protection and the control of daylight radiation, if taken into account, were always implemented flexibly and often adaptively. Thermal and sound insulation are fulfilled in all examined projects. In most cases, these functions were implemented statically. Uncertainty lies in the interpretation of double façades. They are adjustable and have an effect on both functions, but cannot be clearly assigned to the functions. The control of visual contacts is fulfilled in all

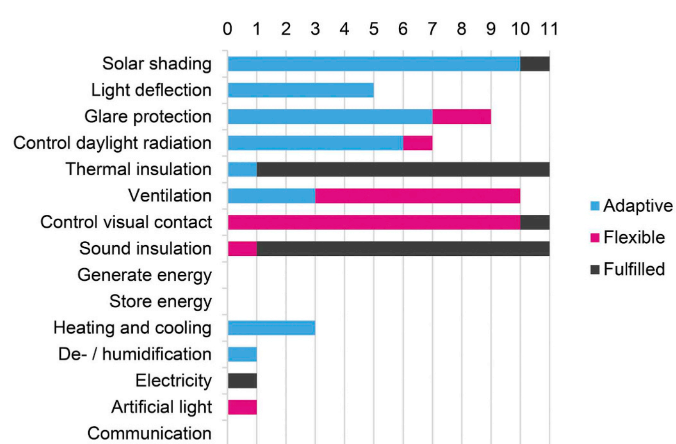

Fig. 25. Cross-case comparison of realized façade functions Figure 26: Joint implementation of fulfilled, flexible and adaptive façade functions.

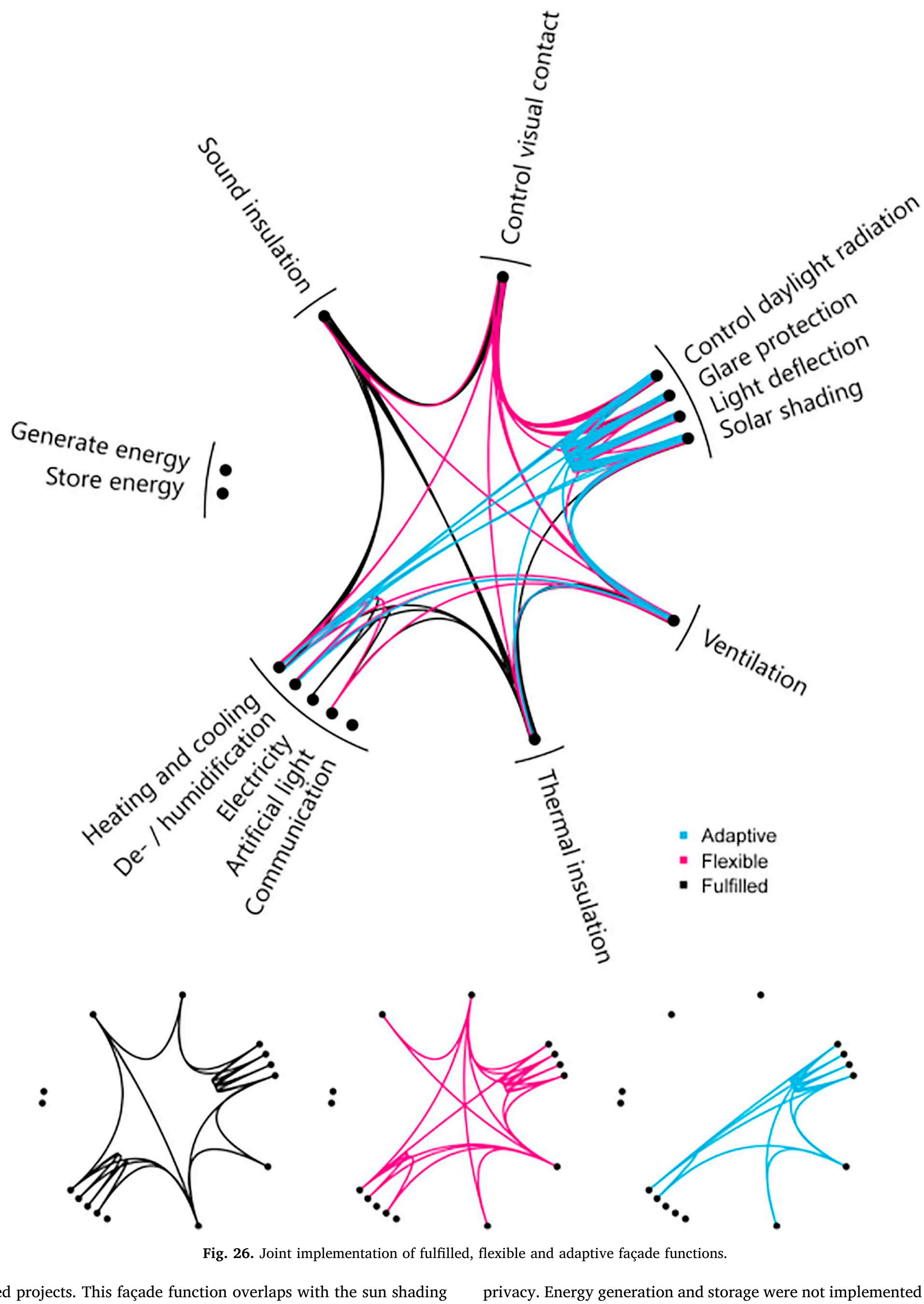

Fig. 26. Joint implementation of fulfilled, flexible and adaptive façade functions.

examined projects. This façade function overlaps with the sun shading component. Since the user has to intervene in the control of the sun shading system to make adjustments, the control of visual contact is recorded as being flexibly implemented. The only exception is the HDI Gerling Headquarters project, in which static parapets provide visual privacy. Energy generation and storage were not implemented in any of the examined projects. Three projects fulfil the façade function of adaptive heating and cooling. One investigated façade fulfils the functtion of humidification and dehumidification of the building. Only the façade of the Capricorn house provides artificial lighting for the

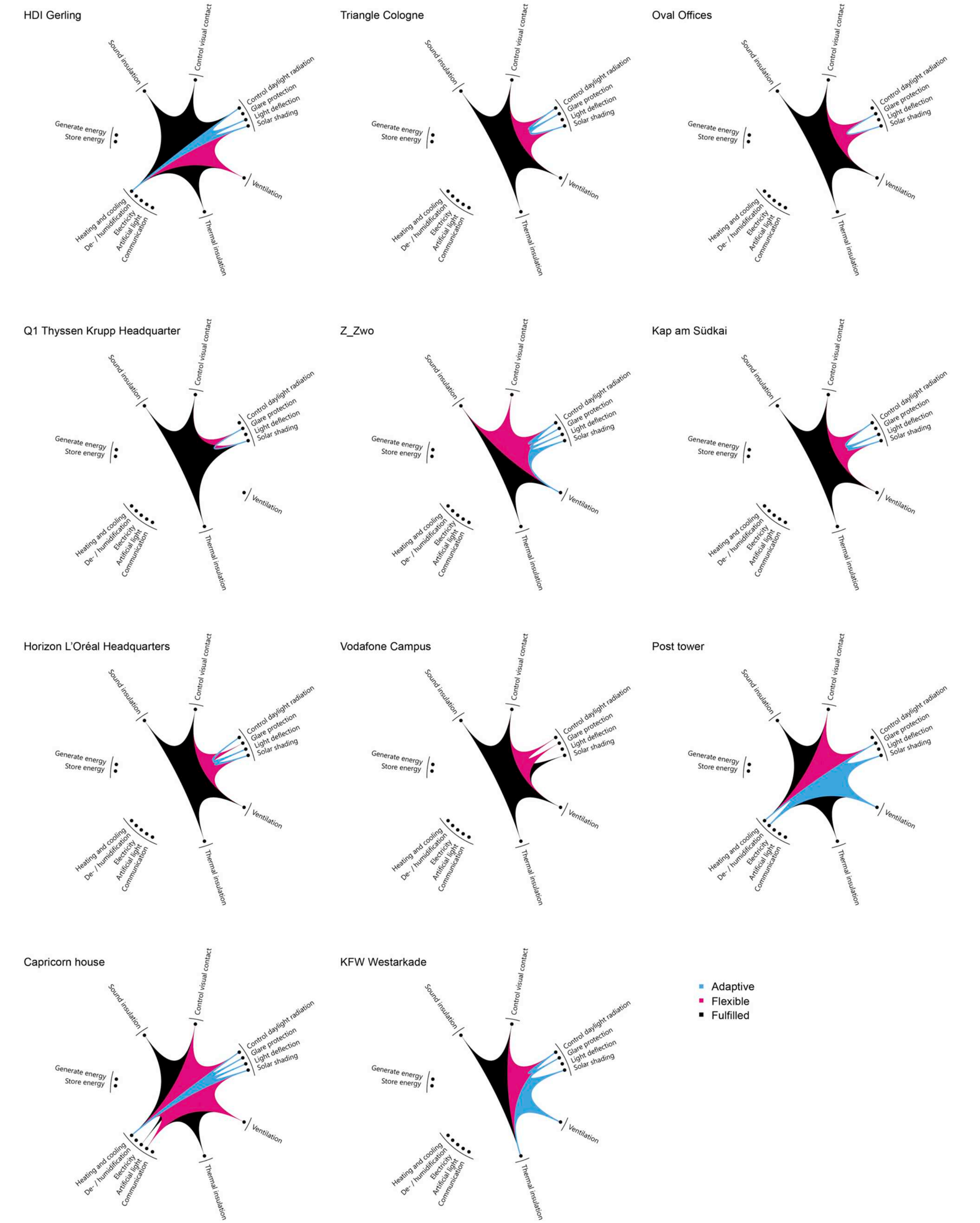

Fig. 27. Jointly implemented façade functions by project.

building. The lighting technology found in some of the projects to provide for media installation is not considered in this compilation.

The radial diagrams in Fig. 26 show which functions are jointly implemented. According to the colour scheme in Fig. 25, a distinction is made between the fulfilled, the flexible and the adaptive façade functions. The overlapping of the connecting lines results in a densification of the

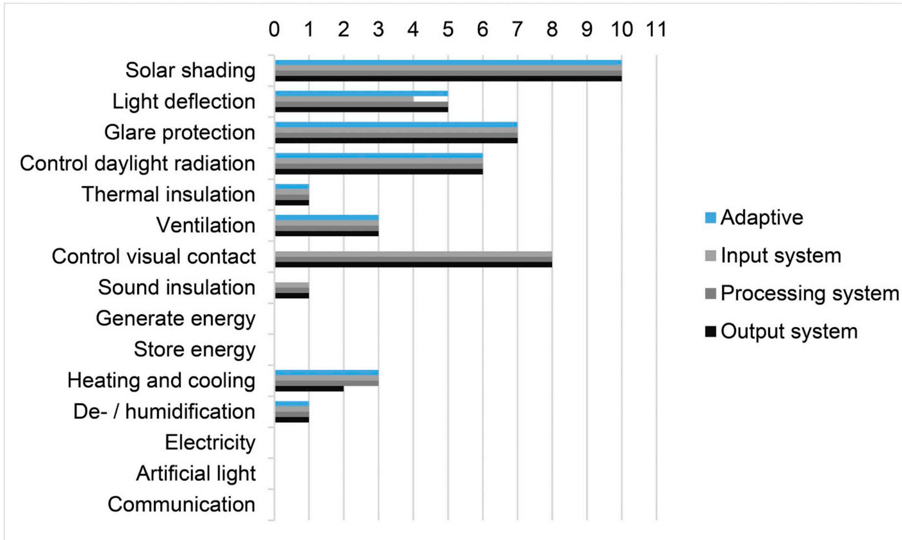

Fig. 28. Automation in the realisation of adaptive façade functions.

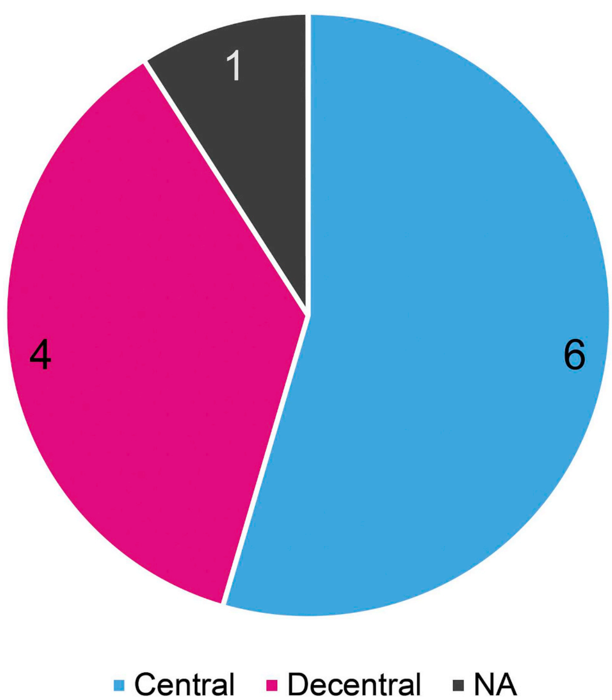

Fig. 29. Relationship between decentralised and central automation.

façade functions, which are implemented together several times. The combined implementation of façade functions, classified as adaptive, is represented by the blue connecting lines. Here, a focus lies on the functions of solar shading, light control, glare protection, and control of daylight radiation in combination with ventilation and heating and cooling. The implementation of these functions often takes place together with the flexible control of visual contacts.

Fig. 27 provides a differentiated view of the jointly fulfilled façade functions, also considering flexibility and adaptivity, organised according to the projects examined.

None of the examined projects feature the application of smart materials. According to the definition by Loonen, et al. [18], the operation of adaptability is to be assessed exclusively as extrinsically. Fig. 28 shows the use of sensors as input systems, controllers as processing systems and existing output systems such as actuators for the implementation of adaptions. All implemented adaptabilities comprise these three aspects of mechatronic systems. Deviations occur, for example, in the function of light deflection, when the control is not based on sensor data but on predefined programming. The control of visual contact is often implemented via automated components in which the user must actively intervene. As in one case of sound insulation, there is no adaptivity recorded, even if an existing automation infrastructure has been found.

The overview of the project data shows that there are different degrees of a decentralised implementation of the control system. Jointly controlled automation can be bundled by floors, sections, rooms, but also by façade elements or individual components. Control systems embedded in a respective façade component could not be determined in any project of this study. Fig. 29 shows that the interview partners classified more than half of the automation examined as centrally controlled. This means that while a processing system is available, there is no integration of the control system into the façade or the façade component.

Most automated adaptive façade functions in this study permit intermediate states or stepless control and are therefore recorded as gradually implemented. Adjustments are carried out at different time intervals. An existing range was determined from adaptations in seconds to adjustments that take place in the course of different seasons.

4. Discussion

The study provides an overview of which functions are considered in practice for a flexible and adaptive implementation of the façade. Each of the examined projects is unique and the building concepts, as well as the façade constructions, are tailored to the respective individual conditions and requirements. A clear distinction of the façade functions in the components assigned to them is only partially possible in the overall view of this study. There is a grey zone in which tasks of the façade overlap in terms of components and technologies. A corresponding scope for interpretation in the assignment of components, façade functions and an automated adaptive implementation remains. However, it is possible to identify tendencies.

The automated adaptive façade functions and corresponding components almost always feature the characteristics of mechatronic systems with existing sensors, actuators and controls. Their control is centrally organised in more than half of the projects. Different organisational forms and intermediate stages of decentralised implementation were identified in the projects that have been assessed as decentralised by the interview partners. As described in the cross-case analysis in Section 3.2, the controls are often combined and bundled in units of different sizes. The distinction formulated by Loonen, et al. [18] between the two extremes central and decentral does not meet the complexity of the possible forms of organisation. Here, further research is needed to assess the decentralisation of an automated façade system. However, the integration of the control system into a façade component was not determined in any of the projects. Although a processing system is basically available and linked to the facade functions, the automated components do not meet the requirement for intelligent cooperation, because they are not embedded as formulated by Wolf [35].

5. Conclusion

The current state-of-the-art in the automation of façades does not yet correspond to the development stage of cyber-physical systems achieved in other application fields, such as in the industry 4.0. The study provides a detailed overview of the automation of adaptive façade functions in building practice as a technical basis for further research and application of cyber-physical systems to the façade. Furthermore, façade functions are identified, which are particularly promising constituents of cyber-physical façades due to their joint automated implementation. The research questions of this study can be answered as follows: all of the projects examined exhibit solar shading, thermal insulation, sound insulation and the control of visual relationships as important climatic functions. Light control, glare protection and daylight irradiation control were taken into account in about half of all projects. Heating and cooling were determined as a function considered in three cases. Support functions such as de-/humidification, electricity, artificial lighting and communication otherwise play a subordinate role and are rarely implemented in the façades. Energy generation and storage, as well as the infrastructure for communication, were not found in any of the façades investigated. Adjustments of the façade functions of ventilation and control of visual relationships often require the intervention of the user and are therefore considered to be predominantly implemented as flexible. Adaptivity is particularly applied to the sun-related functions solar shading, glare protection, control daylight radiation and light deflection. These functions are often solved in combination, for example by using a shared automated component such as a lamella system. As described in the cross-case analysis, focal points of the jointly adaptively implemented functions can be identified. They include the above-mentioned functions solar shading, glare protection, control daylight radiation and light deflection, which are often implemented adaptively together with ventilation and the heating and cooling functions. The use of smart materials was not found in any of the projects investigated; instead, automation technology is used in all cases in which the adaptivity of a façade function is realized.

6. Future research

Since adaptations of the façade are largely implemented on a mechatronic basis, a further examination of networking strategies between individual functions in the sense of intelligent technical systems appears very promising. In view of the identified, intermediate steps of decentralised controls, future investigations are required that concentrate on the organisation of the automation concepts. The technical possibilities of decentrally organized and cooperating façade functions has not yet been clarified. The functions sun protection, glare protection, control of daylight irradiation and light control, ventilation as well as heating and cooling are often jointly automated and adaptively implemented. Therefore, these functions are particularly interesting for the further investigation of the technical feasibility of networking strategies within a cyber-physical façade system.

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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