Thinking-Skins

Cyber-physical systems as foundation for intelligent adaptive façades

Jens Böke

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ThinkingSkins

Cyber-physical systems as foundation for intelligent adaptive façades

Dissertation

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at Delft University of Technology
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chair of the Board for Doctorates
to be defended publicly on
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by

Jens BÖKE
Master of Arts in Architecture, FH Münster - University of Applied Sciences, Germany
born in Steinheim (Westf.), Germany

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This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof.dr. U. Knaack	Delft University of Technology, promotor
Prof. M. Hemmerling	Cologne University of Applied Sciences, Germany, copromotor

Independent members:

Prof.dr. T. Klein	Delft University of Technology
Prof.dr. O. Tessmann	Technical University (TU) of Darmstadt
Prof. P. J. Russell	Delft University of Technology
Prof. D. Arztmann	OWL University of Applied Sciences and Arts
Prof. U. Blum	FH Münster – University of Applied Sciences
Prof.dr. U. Pottgiesser	Delft University of Technology, reserve member

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Preface

‘We can only see a short distance ahead, but we can see plenty there that needs to be done.’ (Alan Turing, 1950)

The examination of the intelligent building envelope as a thinking skin in this dissertation originates from an equally great fascination for architecture and for the related use of computer technologies.

The availability of computation in architecture enables new formal expressions and advanced constructions, which previously, could be formulated only as an unbuildable utopia. What a wonderful new world with unimagined possibilities! Before starting the research project *ThinkingSkin*s, I gathered experiences in the field of computation in architecture by examining digital tools used in the design process of building projects. Here, the computer enables the comprehensive negotiation of relevant project data, for example by the use of parametric design methods. In addition to the three-dimensional representation of the design result, parametric models are able to map underlying relationships and dependencies between individual design aspects. In a parametric design, important influencing factors and design properties are recorded as parameters and related to each other, for example in a flow-based visual programming sequence. The task in the application of such a design strategy is related less to the conception of the specific result, but rather to the development of the parametric design process moving into focus. Such design processes highlight the unrestricted adaptability of the digital environment, because once the dependencies within a project are defined, the model dynamically adapts to changing parameters. In this context, the self-conducted SunSys project, which is referenced in the introduction, can be regarded as a preliminary study for the dissertation. An experience gained from the implementation of the project lay in the discrepancy between the dynamic parametric design model and its realisation, in which the adaptability was lost due to a static implementation. Against this background, the *ThinkingSkin*s research project is driven by the desire to transfer the dynamic negotiation of design parameters and the inherent optimisation potential to realized physical constructions.

The façade is a particularly interesting application field. It not only determines the external appearance and aesthetics, but also significantly influences the quality of living and the energetic performance of a building. The façade constitutes the

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interface between the external environment and the interior and is confronted both with the dynamics of changing climatic influences and the varying user requirements in the operation of the building. The application of a parametric approach as formulated above appears promising but, at the same time, challenging in view of the range of resulting influencing factors and requirements to be negotiated. The combination of these considerations contributed to the choice of the actual research topic in the field of façades.

Many new technologies and innovations emerge in the course of the current digitalization. About forty years after the introduction of the Internet in the 1980s, networking physical objects towards an Internet of Things is now at the focus of development. Even though we are at the beginning of this development, changes are already visible. Far-reaching innovations, such as smart homes, autonomous driving and cargo drones, are in sight on the horizon. At the same time, there are major global challenges, including the supply of an exponentially growing world population, the consumption of non-renewable raw materials, and the necessity to deal with the consequences of climate change, among others. This results in a responsibility to use available resources and technologies efficiently and effectively. The holistic scope and effects of both the introduced technologies and upcoming challenges cannot yet be predicted. Therefore, the quote by Turing (1950) appears highly topical today. The enthusiasm for emerging technologies as well as an awareness of a meaningful and appropriate use determine the attitude in the elaboration of this project.

The research project *ThinkingSkin*s has an explorative nature and is curiosity driven. Decisions on individual research objectives were based on the findings of the individual sub-projects during the course of the work. Thus, the complete result as documented in this book was not foreseeable in the process. Many accompanying activities were connected with the research, which additionally shaped the overall project. These include, for example, the hosting of and participation in different workshops and conferences as well as the integration of the research topic into academic teaching. Corresponding events are documented throughout the doctoral thesis as side notes. For me, writing this thesis was an exciting journey, during which I learned a lot about the elaborated subject and also about myself. I would like to thank everyone who accompanied and supported me on this journey.

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Cordial thanks are regarded to my family, namely Angelika, Jörg and Andrea Böke. Their backup made this project and many steps towards it possible in the first place. I also thank my grandmother Toni, who was always convinced about the success of this project and pushed me to finalize it.

Many people have played an important role in the successful completion of this doctoral thesis. I would like to highlight Tillmann Klein, Thaleia Konstantinou, Alejandro Prieto Hoces and all other peers from the Architectural Façades & Products research group. The critical discussions in the various group meetings made an important contribution to the result presented here. Special thanks belong to Holger Strauß and Linda Hildebrand, who particularly influenced the beginning of this project with their support and orientation, and also to Christian Möllering and Boris Bähre for many inspiring and helpful discussions. Usch Engelmann deserves great thanks for her linguistic support in proofreading.

Thanks to all interview partners and their respective companies who contributed to the *ThinkingSkin*s project by answering project-related questions. In view of the ongoing daily business, their eagerness to support this research is by no means self-evident and highly appreciated.

The development of this project was influenced by different organizational and scientific employments at universities. In particular, the responsibility as coordinator of the postgraduate Master's programme Computational Design and Construction at the Ostwestfalen-Lippe University of Applied Sciences provided an inspiring environment for the start of the thesis. Many thanks go to Claudia Fries for establishing the supportive working atmosphere of the Werkstatt Emilie in this context. The same applies to the parallel employment in the ConstructionLab of the university, where I am particularly grateful for the support by Uta Pottgiesser. I also

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thank the Faculty of Architecture and especially the Team CODE ARCH of the Cologne University of Applied Sciences for an exciting time with many new impulses. Here I would like to highlight my former colleagues Philipp Meise, Max Salzberger and Simon Maris as well as the tutors of the CAM laboratory I was responsible for. In both working environments I have experienced a lot of support and assist for my research activities from professors. Special thanks go to Fabian Storch and Thorsten Burgmer for their readiness and support in partial investigations of the project.

Furthermore I thank all friends who are still friends despite many cancelled events and missed meetings. Thanks belong to Helge Hagedorn and Dennis Dreimann for many years of friendship. Thanks are also regarded to Bernd Benkel, Pia Peters and Sebastian Christiansen, Tristan Fürstenberg and Sascha Römer, and to all you others.

Last but not least my deepest thanks belong to Katharina Bröckling. She is the strong woman at my side and has supported me in many difficult situations even when I transformed our common living room into a laboratory and workshop. Thank you for your trust and patience – we are a powerful team in which your love makes me the person I am today.

Cologne, April, 2020

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Kranhaus Süd by BRT - Bothe Richter Teherani architects in Cologne, Germany

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Summary

Under the guiding concept of a thinking skin, the research project examines the transferability of cyber-physical systems to the application field of façades. It thereby opens up potential increases in the performance of automated and adaptive façade systems and provides a conceptual framework for further research and development of intelligent building envelopes in the current age of digital transformation.

The project is characterized by the influence of digital architectural design methods and the associated computational processing of information in the design process. The possible establishment of relationships and dependencies in an architecture understood as a system, in particular, are the starting point for the conducted investigation. With the available automation technologies, the possibility of movable building constructions, and existing computer-based control systems, the technical preconditions for the realisation of complex and active buildings exist today. Against this background, dynamic and responsive constructions that allow adaptations in the operation of the building are a current topic in architecture. In the application field of the building envelope, the need for such designs is evident, particularly with regards to the concrete field of adaptive façades. In its mediating role, the façade is confronted with the dynamic influences of the external microclimate of a building and the changing comfort demands of the indoor climate. The objective in the application of adaptive façades is to increase building efficiency by balancing dynamic influencing factors and requirements. Façade features are diverse and with the increasing integration of building services, both the scope of fulfilled façade functions and the complexity of today's façades increase. One challenge is the coordination of adaptive functions to ensure effective reactions of the façade as a complete system. The *ThinkingSkin*s research project identifies cyber-physical systems as a possible solution to this challenge. This involves the close integration of physical systems with their digital control. Important features are the decentralized organization of individual system constituents and their cooperation via an exchange of information. Developments in recent decades, such as the miniaturisation of computer technology and the availability of the Internet, have established the technical basis required for these developments. Cyber-physical systems are already employed in many fields of application. Examples are decentralized energy supply, or transportation systems with autonomous vehicles. The influence is particularly evident in the transformation of the industrial sector to Industry 4.0, where formerly

mechatronic production plants are networked into intelligent technical systems with the aim of achieving higher and more flexible productivity.

In the *ThinkingSkin*s research project it is assumed that the implementation of cyber-physical systems based on the role model of cooperating production plants in IIndustry 4.0 can contribute to an increase in the performance of façades. Accordingly, the research work investigates a possible transfer of cyber-physical systems to the application field of building envelopes along the research question:

- **How can cyber-physical systems be applied to façades, in order to enable coordinated adaptations of networked individual façade functions?**

To answer this question, four partial studies are carried out, which build upon each other. The first study is based on a literature review, in which the understanding and the state-of-the-art development of intelligent façade systems is examined in comparison to the exemplary field of application of cyber-physical systems in the manufacturing industry. In the following partial study, a second literature search identifies façade functions that can be considered as components of a cyber-physical façade due to their adaptive feasibility and their effect on the façade performance. For the evaluation of the adaptive capabilities, characteristics of their automated and adaptive implementation are assigned to the identified façade functions. The resulting superposition matrix serves as an organizational tool for the third investigation of the actual conditions in construction practice. In a multiple case study, realized façade projects in Germany are examined with regard to their degree of automation and adaptivity. The investigation includes interviews with experts involved in the projects as well as field studies on site. Finally, an experimental examination of the technical feasibility of cyber-physical façade systems is carried out through the development of a prototype. In the sense of an internet of façade functions, the automated adaptive façade functions ventilation, sun protection as well as heating and cooling are implemented in decentrally organized modules. They are connected to a digital twin and can exchange data with each other via a communication protocol.

The research project shows that the application field of façades has not yet been exploited for the implementation of cyber-physical systems. With the automation technologies used in building practice, however, many technical preconditions for the development of cyber-physical façade systems already exist. Many features of such a system are successfully implemented within the study by the development of a prototype. The research project therefore comes to the conclusion that the application of cyber-physical systems to the façade is possible and offers a promising potential for the effective use of automation technologies. Due to the

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lack of artificial intelligence and machine learning strategies, the project does not achieve the goal of developing a façade in the sense of a true *ThinkingSkin* as the title indicates. A milestone is achieved by the close integration of the physical façade system with a decentralized and integrated control system. In this sense, the researched cyber-physical implementation of façades represents a conceptual framework for the realisation of corresponding systems in building practice, and a pioneer for further research of *ThinkingSkin*s.

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Samenvatting

Vanuit het concept van de thinking skin onderzoekt dit project de implementatie van cyber-fysische systemen voor geveltoepassingen. Het faciliteert daarmee de mogelijkheid om de prestaties van geautomatiseerde en adaptieve gevelsystemen te verbeteren. Het biedt in de huidige tijd van digitale transformatie ook een conceptueel kader voor verder onderzoek aan en ontwikkeling van intelligente bouwschillen.

Het project kenmerkt zich door de invloed van digitale architectonische ontwerpmethoden en de daarmee samenhangende rekenkundige informatieverwerking in het ontwerpproces. Het uitgangspunt van het verrichte onderzoek is vooral de mogelijke totstandkoming van relaties en hun onderlinge samenhang in een als systeem bekeken architectuur. Tegenwoordig zijn de technische randvoorwaarden om complexe en dynamische gebouwen te realiseren aanwezig in de vorm van de beschikbare automatiseringstechnologie, het kunnen beschikken over beweegbare bouwconstructies en de bestaande computergestuurde besturingssystemen. In deze context vormen dynamische en responsieve constructies, die aanpassingen in de werking van het gebouw mogelijk maken, een actueel onderwerp in de architectuur. In het toepassingsgebied van de gebouwschil is de behoefte aan zulke ontwerpen sterk aanwezig, vooral op het vlak van adaptieve gevels. In zijn regulerende rol wordt de gevel blootgesteld aan de dynamische invloeden van het externe microklimaat van een gebouw en de veranderende comforteisen aan het binnenklimaat. Het doel van de toepassing van adaptieve gevels is het verhogen van de gebouwefficiëntie door een balans te vinden tussen dynamische invloedfactoren en eisen. Geveleigenschappen zijn divers en met de toenemende integratie van gebouwfaciliteiten nemen zowel de reikwijdte van de vervulde gevelfuncties als de complexiteit van hedendaagse gevels toe. Er ligt een uitdaging in het coördineren van aanpasbare functies om een effectieve respons van de gevel als een compleet systeem te bewerkstelligen. Het *ThinkingSkin*s onderzoeksproject identificeert cyber-fysische systemen als mogelijke oplossing van deze uitdaging. Het gaat hierbij om de nauwe interactie van fysieke systemen met hun digitale besturing. Belangrijke eigenschappen zijn de decentrale organisatie van afzonderlijke systeemonderdelen en hun samenwerking door uitwisseling van informatie. De ontwikkelingen van de afgelopen decennia, zoals de miniaturisering van de computertechnologie en de beschikbaarheid van het internet, hebben voor de nodige technische basis van deze ontwikkeling gezorgd. Cyber-fysische systemen

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kennen al vele toepassingen. Voorbeelden zijn de decentrale energievoorziening en transportsystemen met zelfrijdende voertuigen. De invloed van cyber-fysische systemen is vooral zichtbaar in de transformatie van de industriële sector naar Industry 4.0, waarbinnen de voorheen mechatronische productie-installaties in intelligente technische systemen worden genetwerkt met als doel een hogere en meer flexibele productiviteit.

Het *ThinkingSkin*s onderzoeksproject gaat ervan uit dat de implementatie van cyber-fysische systemen, gebaseerd op het rolmodel van samenwerkende productie-installaties in Industry 4.0, kan bijdragen aan een verhoging van gevelprestaties. Dit onderzoek bestudeert dan ook de mogelijke overdracht van cyber-fysische systemen naar de toepassing op gebouwschillen aan de hand van de volgende onderzoeksvraag:

- **Hoe kunnen cyber-fysische systemen op gevels worden toegepast om gecoördineerde aanpassingen van genetwerkte individuele gevelfuncties mogelijk te maken?**

Om deze vraag te beantwoorden zijn vier op elkaar voortbouwende deelstudies uitgevoerd. De eerste studie is gebaseerd op een literatuuronderzoek, waarin het begrip en de state-of-the-art ontwikkeling van intelligente gevelsystemen wordt beschouwd in vergelijking met de voorbeeldtoepassing van cyber-fysische systemen in de maakindustrie. In de daaropvolgende deelstudie identificeert een tweede literatuuronderzoek de gevelfuncties die kunnen worden overwogen als onderdelen van een cyber-fysische gevel vanwege hun aanpasbaarheid en hun effect op de gevelprestatie. De karakteristieken van hun geautomatiseerde en adaptieve implementatie worden toegewezen aan de onderscheiden gevelfuncties om hun aanpasbaarheid te evalueren. De resulterende superpositiematrix dient als organisatorisch instrument voor het derde onderzoek naar de daadwerkelijke omstandigheden in de bouwpraktijk. In een meervoudige casestudy worden in Duitsland gerealiseerde gevelprojecten onderzocht op hun automatiseringsgraad en aanpasbaarheid. Het onderzoek omvat zowel interviews met bij de projecten betrokken deskundigen als praktijkonderzoek ter plaatse. Ten slotte is door middel van de ontwikkeling van een prototype experimenteel onderzoek gedaan naar de technische haalbaarheid van cyber-fysische gevelsystemen. Vanuit een internet van gevelfuncties bezien worden de geautomatiseerde adaptieve gevelfuncties van ventilatie, zonwering, verwarming en koeling in decentraal georganiseerde modules geïmplementeerd. Ze zijn verbonden met een digital twin en kunnen via een communicatieprotocol gegevens met elkaar uitwisselen.

Uit het onderzoek blijkt dat de toepassing op gevels nog niet is benut voor de implementatie van cyber-fysische systemen. Met de automatiseringstechnologieën die in de bouwpraktijk worden gebruikt, zijn veel van de technische randvoorwaarden voor de ontwikkeling van cyber-fysische gevelsystemen al aanwezig. Veel functies van een dergelijk systeem zijn met succes geïmplementeerd in de ontwikkeling van het prototype. Het onderzoeksproject komt dan ook tot de conclusie dat de toepassing van cyber-fysische systemen op gevels mogelijk is en veelbelovend is voor een effectief gebruik van automatiseringstechnologieën. Door het gebrek aan kunstmatige intelligentie en machine learning-strategieën heeft het project niet zijn uiteindelijke doel bereikt om een gevel te ontwikkelen als een echte *ThinkingSkin*, zoals de projecttitel aangeeft. Met de nauwkeurige integratie van het fysieke gevelsysteem in een decentraal en geïntegreerd besturingssysteem wordt een mijlpaal bereikt. In die zin vormt de onderzochte cyber-fysische implementatie van gevels een conceptueel kader voor de realisatie van bijbehorende systemen in de bouwpraktijk. Het project nodigt uit tot verder onderzoek aan *ThinkingSkin*s.

Zusammenfassung

Unter dem Leitmotiv einer denkenden Haut (‘thinking skin’) untersucht die Forschungsarbeit eine Übertragbarkeit cyber-physikalischer Systeme auf das Anwendungsfeld der Fassade. Damit erschließt sie potenzielle Leistungssteigerungen von automatisierten, adaptiven Fassadensystemen und schafft einen konzeptionellen Rahmen für die weitere Erforschung und Entwicklung intelligenter Gebäudehüllen im aktuellen Zeitalter der digitalen Transformation.

Das Projekt ist geprägt von den Einflüssen digitaler Entwurfsmethoden auf die Architektur und der damit verbundenen computer-basierten Verhandlung von Informationen im Entwurfsprozess. Insbesondere die mögliche Herstellung von Beziehungen und Abhängigkeiten in einer als System verstandenen Architektur sind Ausgangspunkt für die geführte Auseinandersetzung. Mit verfügbaren Automatisierungstechnologien, der Möglichkeit beweglicher Baukonstruktionen und computer-basierten Steuerungen bestehen heute die technischen Voraussetzungen für die Realisierung komplexer und aktiver Gebäude. Vor diesem Hintergrund sind dynamische und reaktionsfähige Konstruktionen, die Anpassungen im Betrieb des Gebäudes ermöglichen, ein aktuelles Thema in der Architektur. Im Anwendungsgebiet der Gebäudehülle zeigt sich der Bedarf an solchen Bauformen im konkreten Themenfeld adaptiver Fassaden. Die Fassade ist in ihrer Vermittlerrolle mit den dynamischen Einflüssen des äußeren Mikroklimas eines Gebäudes und den wechselnden Komfortansprüchen an das Innenraumklima konfrontiert. Zielsetzung in der Anwendung adaptiver Fassaden ist die Steigerung der Gebäudeeffizienz durch die Ausbalancierung dynamischer Einflussfaktoren und Anforderungen. Ihr Aufgabenspektrum ist vielfältig und mit der zunehmenden Integration von Haustechnik steigen sowohl der Umfang erfüllter Fassadenfunktionen als auch die Komplexität heutiger Fassaden. Eine Herausforderung liegt hier in der Abstimmung adaptiver Funktionen zu effektiven Reaktionen der Fassade als Gesamtsystem. Im Forschungsprojekt *ThinkingSkin*s werden cyber-physikalische Systeme als mögliche Lösung dieser Herausforderung identifiziert. Dabei handelt es sich um die enge Verzahnung physikalischer Systeme mit ihrer digitalen Kontrolle. Wichtige Merkmale sind die dezentrale Organisation einzelner Systembestandteile und deren Kooperation über einen Austausch von Informationen. Entwicklungen der vergangenen Jahrzehnte, wie beispielsweise die Miniaturisierung von Computertechnik und die Verfügbarkeit des Internets, haben dafür die Voraussetzungen geschaffen. Cyber-physikalische Systeme kommen bereits in vielen

Anwendungsfeldern zum Einsatz. Beispiele sind die dezentrale Energieversorgung oder das Transportwesen mit autonomen Fahrzeugen. Der Einfluss solcher Systeme zeigt sich besonders in der Transformation des Industriesektors zu einer Industrie 4.0. Hier werden vormals mechatronische Fertigungsanlagen mit dem Ziel einer höheren und flexibleren Produktivität zu intelligenten technischen Systemen vernetzt.

Im Forschungsprojekt *ThinkingSkin*s wird davon ausgegangen, dass die Umsetzung als cyber-physikalisches System nach dem Vorbild kooperierender Produktionsanlagen in der Industrie 4.0 zu einer Leistungssteigerung der Fassade beitragen kann. Die Forschungsarbeit untersucht dementsprechend eine mögliche Übertragung cyber-physikalischer Systeme auf das Anwendungsfeld der Gebäudehülle unter der Fragestellung:

- **Wie können cyber-physikalische Systeme auf Fassaden angewendet werden, um eine koordinierte Anpassung einzelner, vernetzter Fassadenfunktionen zu ermöglichen?**

Für die Beantwortung der Fragestellung werden vier aufeinander aufbauende Teiluntersuchungen durchgeführt. Die erste Studie basiert auf einer Literaturrecherche, in der das Verständnis und der Entwicklungsstand intelligenter Fassadensysteme im Vergleich zu dem beispielhaften Anwendungsfeld cyber-physikalischer Systeme in der Industrie überprüft werden. In der folgenden Teiluntersuchung werden im Rahmen einer zweiten Literaturrecherche Fassadenfunktionen ermittelt, die aufgrund ihrer adaptiven Umsetzbarkeit und ihrer Auswirkung auf die Leistungsfähigkeit der Fassade als Bestandteile einer cyber-physikalischen Fassade in Frage kommen. Für die Bewertung der adaptiven Fähigkeiten werden den identifizierten Fassadenfunktionen Charakteristika ihrer automatisierten und adaptiven Umsetzung zugewiesen. Die resultierende Überlagerungsmatrix dient als organisatorisches Werkzeug für die dritte Untersuchung der tatsächlichen Voraussetzungen in der Baupraxis. In einer multiplen Fallstudie werden darin realisierte Fassadenprojekte in Deutschland hinsichtlich ihrer Automatisierung und Adaptivität überprüft. Die Untersuchung beinhaltet die Befragung projektbeteiligter Experten sowie Feldstudien vor Ort. Abschließend erfolgt eine experimentelle Auseinandersetzung mit der technischen Realisierbarkeit cyber-physikalischer Fassadensysteme in der Entwicklung eines Prototyps. Im Sinne eines Internets von Fassadenfunktionen werden darin die automatisiert adaptiven Fassadenfunktionen Lüften, Sonnenschutz und Heizen und Kühlen in dezentral organisierten Modulen umgesetzt. Sie sind an einen digitalen Zwilling angebunden und können über ein Kommunikationsprotokoll Daten miteinander austauschen.

Die Forschungsarbeit zeigt, dass das Anwendungsfeld der Fassade bislang nicht für die Umsetzung cyber-physikalischer Systeme erschlossen wurde. Mit den in der Baupraxis eingesetzten Automatisierungstechnologien bestehen jedoch bereits viele Voraussetzungen für die Entwicklung cyber-physikalischer Fassadensysteme. Viele Merkmale eines solchen Systems konnten in der durchgeführten Prototypentwicklung erfolgreich umgesetzt werden. Das Forschungsprojekt kommt deshalb zu dem Ergebnis, dass die Anwendung cyber-physikalischer Systeme auf die Fassade möglich ist und ein vielversprechendes Potential für den effektiven Einsatz eingebrachter Automatisierungstechnologien bietet. Aufgrund fehlender Strategien künstlicher Intelligenz und des maschinellen Lernens erreicht das Projekt nicht das im Titel genannte Ziel einer Fassade im Sinne einer denkenden Haut (*ThinkingSkin*). Durch die enge Verzahnung des physikalischen Fassadensystems mit einer dezentralen und integrierten Steuerung wird ein Etappenziel erreicht. In diesem Sinne stellt die erforschte cyber-physikalische Umsetzung von Fassaden einen konzeptionellen Rahmen für die Realisierung entsprechender Systeme in der Baupraxis und einen Wegbereiter für die weitere Erforschung von *ThinkingSkin*s dar.

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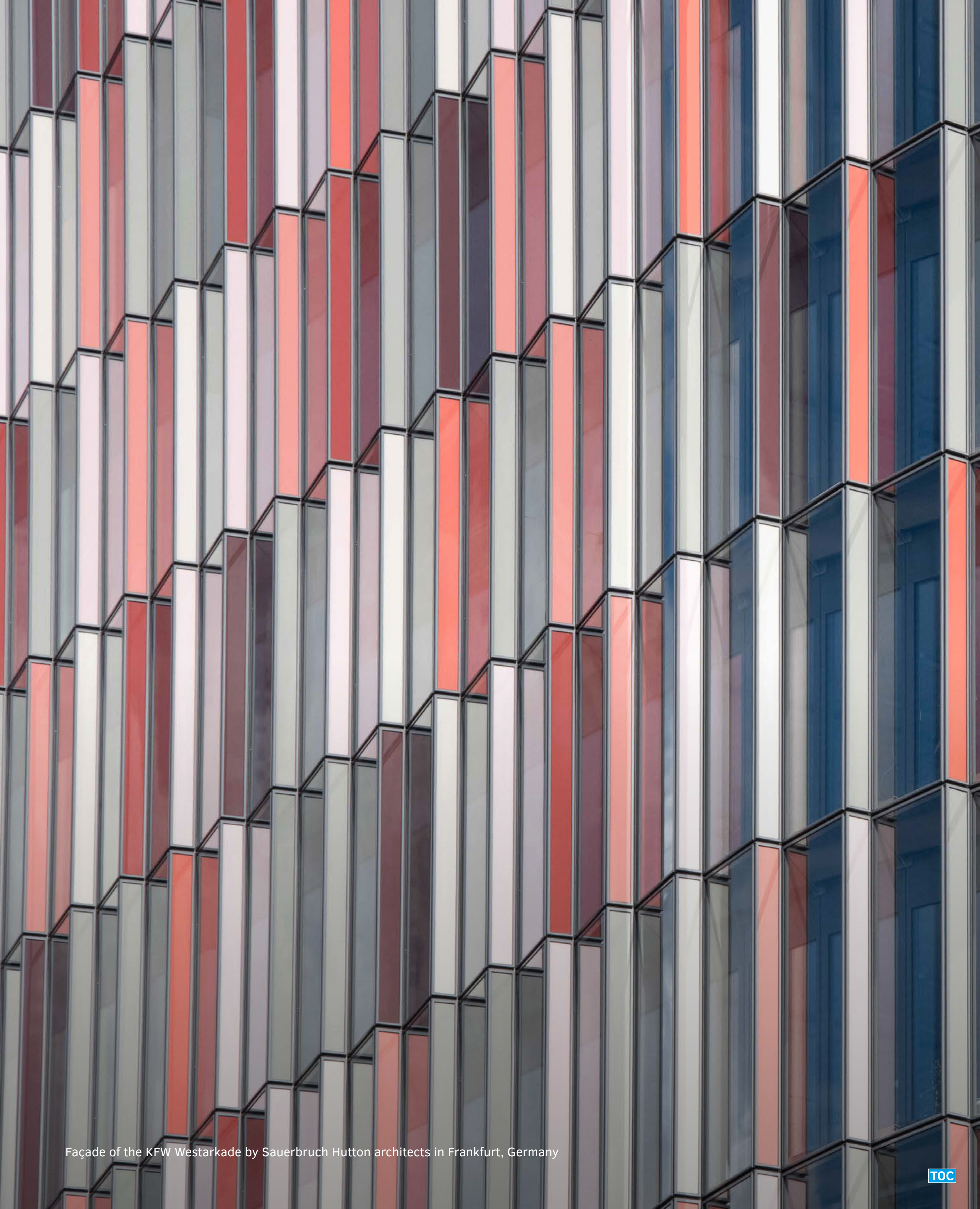

Façade of the KFW Westarkade by Sauerbruch Hutton architects in Frankfurt, Germany

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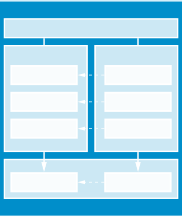
1 Introduction

2 Literature review

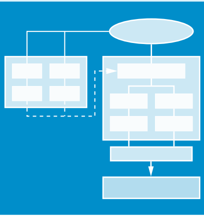
State-of-the-art of intelligent building envelopes in the context of intelligent technical systems



Research focus and knowledge gap

3 Literature review

Superposition matrix for the assessment of performance-relevant adaptive façade functions



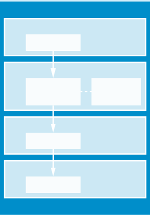
Superposition matrix

Practical result

Assessment tool for automated adaptive façades

4 Multiple case study analysis

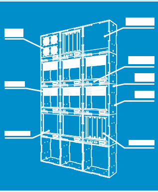
Automated adaptive façade functions in practice - Case studies on office buildings



Priority list of extensively automated façade functions

5 Experiment

Prototype of a cyber-physical façade system



Prototype

Practical result

Example architecture for a Cyber-physical façade system

6 Conclusion

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1 Introduction

1.1 Vision of a thinking skin

Arch+ is a German professional journal with a long tradition and a good reputation for dealing with questions of architectural theory. In 1990, issue number 104 of the architecture magazine Arch+ deals with the topic of ‘architecture as intelligent skin’. The discussion conducted therein provides a foundation for the research work presented here. In his article, Murphy (1990) describes his point of view of an existing analogy of the building and its components to the human anatomy. He answers the central question of whether a building can think, with yes, and he refers this to the ability of the building to respond intelligently to weather conditions and user demands. In this respect, Murphy (1990) formulates the need for a cerebral system that controls and coordinates the complex processes in the interplay of different building components and processes. With his interpretation of a slick skin, he predicts the decentralized organisation of separately controlled zones of the façade. Davies (1981) anticipates many aspects that are decisive for the development of the research project *ThinkingSkin*s. This includes the miniaturisation of technical components, the integration of façade functions into the façade as a multifunctional overall system, and the adaptability of the façade, which can react dynamically to environmental conditions. In this context, he formulates the idea of a ‘polyvalent wall’, illustrated in FIG. 1.1, which in his opinion functions as an environmental diode. Davies understands this to be an intelligent technical network connected with building services that reacts on the basis of environmental information and in awareness of the building’s usage requirements. In the polyvalent wall, Davies sees the development of a building that thinks and communicates by visually representing performance-oriented processes.

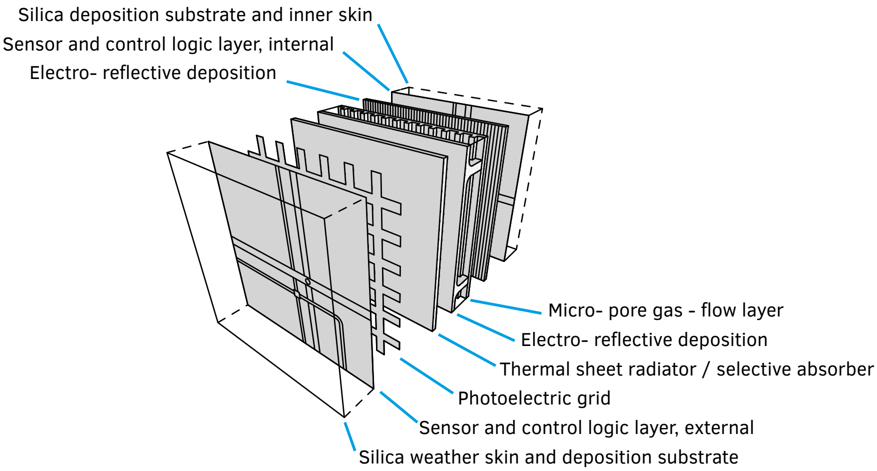

FIG. 1.1 The proposal of a polyvalent wall, adopted from 'A wall for all seasons: create the intelligent environment', by Davies (1981)

Both authors base their estimations on the development stage of the second industrial revolution at that time. The technological achievements that have actually been reached in the field of computer sciences in recent years, such as the miniaturization and performance enhancement of computing units and electronic components, and in particular the possible networking of physical units to an Internet of Things (IOT), which was anticipated by neither Murphy nor Davieshave now opened up a new perspective in the consideration of intelligent architecture.

In the perspective of the research project presented here, the following vision of façades with new and far-reaching capabilities is associated with the concept of a thinking skin: Such a building skin collects extensive information about its environment and is able to process this data into goal-oriented, negotiated decisions. Its motivation lies in an increase of the building performance, while the visualisation of processes is of secondary importance. As a holistic system, the thinking skin initiates coordinated measures of the façade in real time according to the prevailing environmental conditions and indoor comfort requirements. It works as an organism, consisting of decentrally organized units that pursue individual interests according to their respective functions. Information is exchanged between these units by a communication system. In analogy to the Internet of Things, the networking leads to an internet of façade functions. FIG. 1.2 diagrammatically illustrates this idea of a system of networked façade functions between the climatic outside conditions and the user-related comfort requirements of the interior. A detailed description of both concepts 'thinking' and 'skin' in the sense of this work is given in the following section.

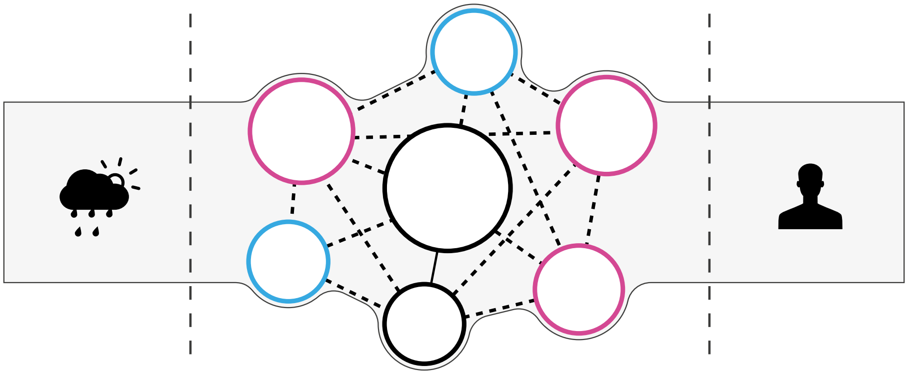

FIG. 1.2 Schematic diagram of networked façade functions between the environmental boundary conditions and the internal comfort requirements

1.2 The notion *ThinkingSkins*

Wigginton and Harris (2002) articulate the notion of a thinking skin in the description of the origin of their book on intelligent skins and in reference to a lecture held in 1985 at the Royal Institute of British Architects (RIBA). In their lecture, they used the term to place the idea of new façade technologies available for implementing a responsive architecture. In 2012, in a joint discussion at RWTH Aachen University, Prof. Dr. Ulrich Knaack and Prof. Peter Russell independently developed the idea of a façade that can decide between its various functions and tasks, and also named this vision of an intelligent façade 'thinking skin'. In the agreement of a research topic it became the guiding idea for the preparation of this thesis. The starting point for the examination of the topic was a workshop held in 2014 at RWTH Aachen under the same title. FIG. 1.3 shows the team of professors and teachers preparing the workshop. Among them are Ulrich Knaack, Sascha Hickert and Thomas Stachelhaus as well as Christian Möllering, who also wrote a dissertation 'A platform for autonomous, façade integrated room control' on this topic (Möllering, 2017).

The title of this project brings the two concepts 'thinking' and 'skin' together. This is associated with an understanding of the building envelope and its functioning, which is to be clarified in the following in view of different possible interpretations.

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FIG. 1.3 Preparation of the workshop ‘Thinking Skins – Smart Façades for Smart Houses’ at the RWTH university in Aachen by P. Russell, 2014

1.2.1 Thinking

The concept of thinking is not easy to grasp, and it is important to note that its assessment formulated here does not claim to be universal, but rather represents a clarification of the understanding in the context of this research project. The term thinking is closely linked to the notion of intelligence, which, according to Murphy (1990), is attributed primarily to humans or more highly developed animals. Accordingly, cognitive sciences explore human and animal cognition (Gudivada, 2016).

Two capacities are characteristic for the human brain; the perception of the environment and the initiation of actions on the environment (Haykin, Amiri, & Fatemi, 2014). Human intelligence affects all mind-related processes on the basis of knowledge about the environment (Raskin, 2015). Among others, Bai (2011) summarizes reasoning, learning from experience, acquiring knowledge, dealing with complex situations and quick reactions to the environment as attributes of intelligent behaviour. In the research of thinking skins, the notion of thinking does not refer to biological but to machine thinking. While human thinking incorporates imagination and the use of natural language, machine intelligence is based on statistical processes. Today, computers are able to perform complex calculations with high processing capacities. It is interesting to know that the term computer did not initially refer to machines, but to people who performed calculations with pen

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and paper (Maeda, 2019). As a mathematician, Alan Turing has been concerned with the question of whether machines can also perform calculations. He defined algorithms and, with the development of the universal Turing Machine, he created a forerunner of today's computers. Thus today, Alan Turing is regarded as the founder of machine thinking (Wegner & Goldin, 2003). The question of whether machines can actually think or whether the processes referred to as thinking are the treatment of consecutive algorithms is still debated by experts (Hoffmann, Folkmer, & Manoli, 2010).

A certain level of autonomy is expected from intelligent machines that must also operate without the direct need for human intervention and survive in uncertain environments. Gausemeier, Anacker, and Czaja (2013) identify autonomy as one aspect of the adaptive behaviour in intelligent technical systems in Industry 4.0. While machines were originally designed to enhance the physical abilities of humans, machines with computing power focus on the extension of cognitive capacities. Especially in relation to computers, a shift in the perception becomes clear. While for other everyday machines and devices, human actions is assumed, in relation to computation this idea shifts to the effect that the computer has independent capacity for action and can therefore carry out operations autonomously. While computation's absolute independency is doubted by Preston (2012), principal system autonomy is still regarded as a characteristic of a thinking façade in the sense of this project.

Artificial intelligence (AI) concerns machine logic according to the model of the human brain. The main objective in the development of AI is to equip systems with the ability to independently solve complex problems (Kirste & Schürholz, 2019). Basically, a distinction can be made between weak and strong artificial intelligence. Weak AI has no internal consciousness and can be understood as an imitation of intelligent behaviour in a certain application domain. Strong AI has a self-awareness and is able to solve complex problems that go beyond the cognitive abilities of the human being (Lexcellent, 2019). The developing history of related strategies parallels the availability of sophisticated computer technologies. Since John McCarthy coined the term artificial intelligence in the 1950s, its concept has evolved significantly (McCarthy, Minsky, & Rochester, 1955). Song and Ma (2010) divide the development process into five phases that can be briefly summarized as following: In the 1950s artificial intelligence was on problem solving while neglecting the relevance of knowledge. The second stage was reached at the end of the 1960s with the introduction of expert systems. In view of the broad access to personal computers, in the 1980s artificial intelligence was able to differentiate objects and distinguish between black and white. The introduction of neural networks is classified by Song and Ma (2010) as the fourth phase. Finally, distributed artificial intelligence was achieved by network technologies, which provided new possibilities such as

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multi-objective problem solving. It represents the fifth development stage. Today different strategies in the implementation of artificial intelligence exist. For example, artificial neuronal networks imitate the operation of nervous systems. Intelligence evolves from the networking of individual nodes which are able to re-organize themselves and offer a certain reliability towards partial damage, due to their decentralized organization (Lexcellent, 2019). Another strategy is fuzzy logic, which imitates human thought processes by representing not only the binary operation of the computer, but also fulfilment degrees of information (Zhaoguang, 1999). An important aspect of intelligent machines is their ability to learn. Machine learning is based on feeding the result of a system back into the algorithm, thereby training the system. LeCun, Bengio, and Hinton (2015) distinguish monitored, unsupervised and reinforced machine learning. Machine learning based on artificial neural networks is referred to as deep learning (Kirste & Schürholz, 2019). The aim of machine learning is to create a knowledge base of the system which, according to Wang and Zatarain (2018), can traditionally be classified in the categories of linguistic, expert based or ontological.

Wegner & Goldin (2003) point out that intelligence is not only based on system-internal calculations, but that interaction is an important requirement for the intelligent behaviour of a system. Also Görz and Schneeberger (2010) estimate intelligence as resulting from interaction, which in their view evolves from simple processes whose cooperation enables complex behaviour. As interaction is strongly related to communication, language also is an important aspect of intelligence. Wiedermann (2012) formulates accordingly that thinking is based on the ability to communicate, and can consequently also be understood as the communication with oneself.

In the understanding of the façade-related research presented here, thinking can be summarized as a machine related process with the following characteristics: Thinking addresses the autonomous operation of the system, incorporating the gathering and intelligent processing of information about the environment, communication and the exchange of information within the system, as well as the initiation of meaningful and coordinated reactions based on perceptions, experiences and knowledge gained.

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Thinking

Processing of information
Autonomous operation
Communication and interaction
Coordination of reactions

Skin

Active organ
Independent mediating
Information recording
Reactions to the environment

FIG. 1.4 Concept diagram of the term composition *ThinkingSkin*s

1.2.2 Skins

The notion ‘skin’ has already been established in architecture as a term for façades and is used in different word compositions, for example: ‘Building skin’, ‘architectural skin’ or ‘intelligent skin’. Such as the term ‘thinking’, the skin has a biological reference as well. The skin is the largest and one of the most complex organs of the human body. It consists of different layers, such as the outer epidermis, the sub-skin designated dermis and a deeper hypodermis. Different cells in each layer perform a variety of functions. Plotczyk and Higgins (2019) identify the protection of the body and internal organs, the regulation of temperature and the prevention of dehydration. The skin has a nervous system that receives information and enables interaction with the environment (Haake, Scott, & Holbrook, 2001).

In the transfer to architecture different interpretations of the concept of an architectural skin are possible. According to Del Grosso and Basso (2010), one lies in the dissolution of previously clearly assigned components such as wall elements and the roof into technically now also organically possible shells. This interpretation is rather negligible for the research project *ThinkingSkin*s, since the building envelope is understood as a mediating layer between the outside and inside of a building, independent of its position and orientation. Carl (2019) differentiates between two skin typologies: on the one hand single-layer shells, which he classifies just as skins, and on the other hand multi-layer systems that interact with the environment as deep skins.

Gruber and Gosztonyi (2010) provide a systematic comparison between the functions of the biological skin and those of the façade as architectural skin. They see the main task of architectural skins in differentiating between the conditions of the environment, identified as ‘chaotic’, and the interior, whose conditions must correspond to human use. In a possible spectrum between absolute isolation of the building and an openness that enables interactions between the interior and exterior, they evaluate the façade implemented as architectural skin as an active mediator. Also Wigginton and Harris (2002) make a direct comparison between the façade and the biological skin. They classify the façade as a third skin after the biological skin of humans and the clothing as a second layer. In the analogy that the biological skin is also connected to the nervous system of the body and firmly integrated into it, they emphasize the necessary connection with the building management system as required holistic view of the entire buildings technical infrastructure. The biological skin continuously reacts to environmental conditions. Carl (2019) names short-term responses, such as sweating for regulating body temperature, as well as long-term evolutionary adaptations, such as colour pigmentation of the skin to provide protection from sunlight. With regard to short-term measures, Wigginton and Harris (2002) differentiate between whether adaptations are consciously carried out according to somatic reactions, or independently, according to the model of the autonomous nervous system in biology. As the biologic skin fulfils many responsive measures autonomously, this aspect can also be transferred to the understanding of architectural skins.

An identified emphasis of building envelopes that correspond to the understanding of a skin lies in their active role and the associated adaptability. Thus, a technical equipment of a façade that is understood as a skin is required to implement the adaptation measures. According to the biological skin, there must be both sensitive components that enable the perception of the environment as well as executive components that carry out adaptations.

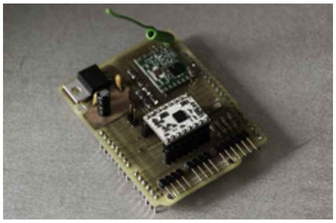
In the understanding of the research project *ThinkingSkin*s, the building skin is an active organism according to the biological model, which independently mediates between the outside environment and the interior of a building. As a skin, this architectural organ represents a physical system consisting of different layers and cells that have far-reaching abilities to record information about the environment and react to it.

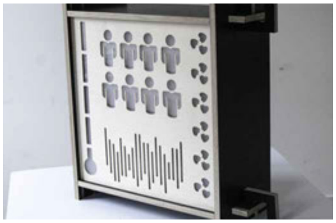
SIDE NOTE: **KICK-OFF WORKSHOP THINKINGSKINS**

The workshop 'Thinking Skins – Smart Façades for Smart Houses' marks a starting point for the research documented in this book and provided inspiration for developing a prototype, as documented in Chapter 5. Jens Böke was member of the supervisor team at the workshop, which took place at the RWTH Aachen in 2014. The task for the students of architecture, product design and information technology was to develop prototypes of automated façades in mixed teams. The design concept had to be aligned with a kinetic construction principle, adaptation strategy and automation technology. In an experimental examination of the topic, innovative concepts for automated façade functions were developed using the production facilities of the university's own FAB-LAB and the Arduino microcontroller platform. Workshop results include, for example, the MOSS SOLAR FAÇADE shown on FIG. A. According to the students' idea, these are rotatable elements equipped with photovoltaic cells on one side and moss vegetation on the opposite side. The PV cells generate electricity, while the mosses clean the air of pollutants in a natural way. Photovoltaic cells only work in sunlight, but the mosses need protection from direct sunlight and water supply, in this case by exposure to rain. The façade detects the prevailing weather conditions via light and rain sensors and aligns the elements accordingly. FIG. C and FIG. D show the results of the cooperating project teams MONITOR and SMART RFDUINO, which aim at the joint operation of a sensor network and the visualization of collected data relevant to the user comfort. Further results of the program were the SMART MESH (FIG. B), an adaptive pneumatic insulation demonstrated by inflatable balloons and the polarizing window (FIG. E), which offers adaptive sun protection via electrochromic glazing (Knaack et al., 2016).


A Moss solar façade


B SmartMesh – Arduino and Android Controlled Pneumatic façade


C SMART RFDUINO


D Project 'Monitor'


E Project 'Polarizing window'

1.3 Background

The achievements in different fields of knowledge form the foundation and the starting point for the execution of this research project. These include the influence of computer technology on architecture and its design processes, the current understanding of dynamic buildings, the façade as an application domain, and the availability of new technologies and strategies in current digitalization. After a general introduction to the subject areas in this section, the differentiated investigation of the current state-of-the-art in the specific focus of this study takes place in Chapter 2: State-of-the-art of intelligent building envelopes in the context of intelligent technical systems.

1.3.1 Computation in architecture

For a long time, pencil, paper and eraser were the architect's decisive instruments. They made it possible to add or remove information in a drawing-based workflow. Over the past decades, the computer has emerged as a central tool for architects, planners, and engineers. It is used in digital design processes, in digital fabrication, but also in the digital control of automation in the operating phase of buildings. With his development of the first Computer Aided Design (CAD) interface Sketchpad, Ivan Sutherland (1964) is regarded as the pioneer in the use of computers in architecture-related design processes . Since the 1980s, the computer is used as a two-dimensional drawing tool in architectural offices with the aim of improving workflows. Since the 1990s, software solutions are available that are also able to represent the design as a three-dimensional model (Hauschild & Karzel, 2010; Kolarevic, 2003). Since then, the use of the computer in design practice mostly corresponds to a computerization. Terzidis (2006) defines computerization as the handling of a previously conceived concept, in which the computer serves as a tool for organising and manipulating entered information. According to Hemmerling (2018), the potential of digital design strategies lies not in the imitation of previously analogue procedures, and Terzidis (2006) doubts whether the mouse-based altering of 3D models can be already regarded as computation. This is because computation incorporates the process of calculation to generate something new and means the application of computers in an open-ended design process leading to unexpected results. Computation is based on explicit and finite instructions called algorithms. Reas, McWilliams, and LUST (2010) compare algorithms with route descriptions that, if strictly followed, lead to a specific destination. They formulate the modular

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structure of extensive algorithms and the possibility of alternative instructions leading to the same goal as characteristics, as well as the integration of assumptions and decisions. Frazer (1995) coined the idea of an evolutionary architecture which relates to generative design processes. While such design methods use evolutionary or learning algorithms to create new content in a morphogenesis, as formulated by Menges and Ahlquist (2011), parametric design concentrates on the interaction between individual design aspects.

According to Woodbury (2010), a main feature of the computer is that, contrary to the classic analogue approach of adding and removing information, it enables the establishment of relationships, both between the design and its contextual requirements, and also between individual qualities and constrains of the concept itself. This is possible by using parametric definitions. Existing software solutions such as the program Grasshopper integrated in Rhinoceros map dependencies within a concept using node-based, visual programming. Therein, geometries and functions are represented as nodes, between which relationships can be established by connecting lines. The overall system of nodes and connecting lines forms the parametric definition. It represents an ‘interactive process model’ formulated by Oxman (2017), in which modified input values, respectively parameters, lead to adapted design results. In an interactive engagement with the parametric definition, the architect designs the logic with which information is negotiated with respect to the desired design result. The parametric definition is linked to the three-dimensional representation, which provides a visual feedback of the resulting design geometry.

An example of a parametric design approach is the SunSys Pavilion project, which was developed in 2009 as a bachelor thesis. In the project, a summer pavilion for the campus Emilie of the Ostwestfalen-Lippe University of Applied Sciences was designed by developing a parametric definition in Grasshopper (Böke, 2009). In addition to the visual programming of the design concept including functional and constructive requirements, the dependency model shown in FIG. 1.5 also incorporates environmental influencing factors. For this purpose, extensive environmental data such as movement profiles and residence times of potential users as well as data on the name-giving solar radiation were collected as shown in FIG. 1.6 at the beginning of the planning process. A main design task was on the selection of relevant parameters and the establishment of relationships in the parametric definition, which also incorporated construction-related constrains resulting from the intended digital fabrication of the design. The negotiation of all relevant information can be understood as an optimization process in which the design result dynamically adapts to changing parameters and dependencies. The transfer of the design into a physical construction was examined in a continuation of the project called SunSys Wall in 2014. The fabrication represents an intervention in this dynamic optimization

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process, which ends with the decision for a specific static implementation. In this manner of thinking, the realized result is only a snapshot in the selection of many possible variations. In the example of the SunSys project, this was a free-form geometry consisting of 400 planar and orthogonally joined individual components. FIG. 1.7 shows the prototype implementation of the developed construction principle as a double-curved wall construction on Campus Emilie in 2014 (Hemmerling & Böke, 2014; Hemmerling, Nether, & Böke, 2018).

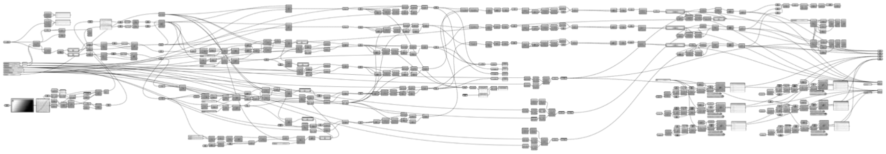

FIG. 1.5 Parametric definition of the SunSys project in Grasshopper 3D

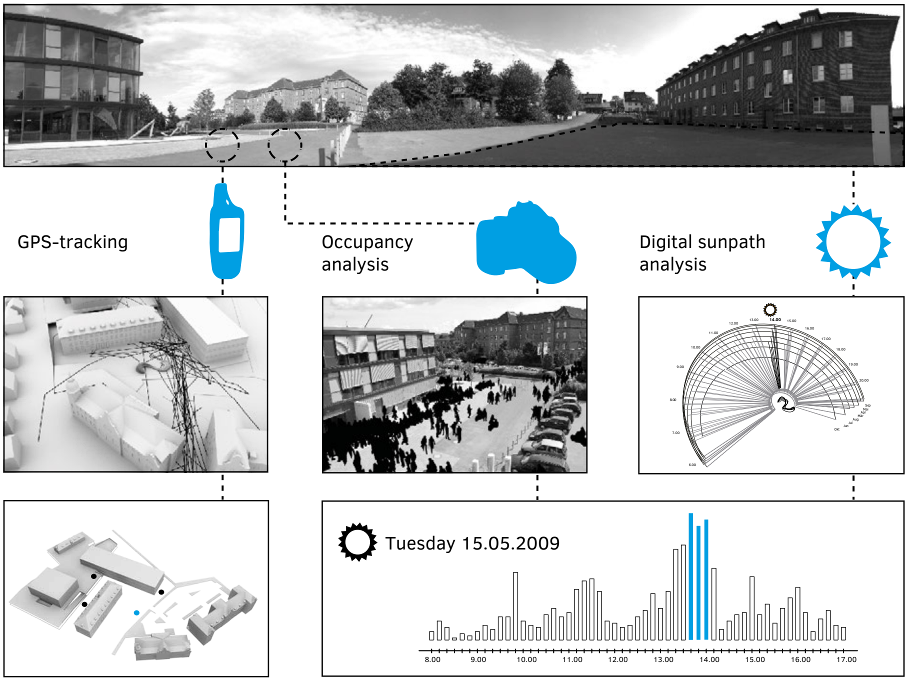

FIG. 1.6 Recording of environmental data used as project parameters

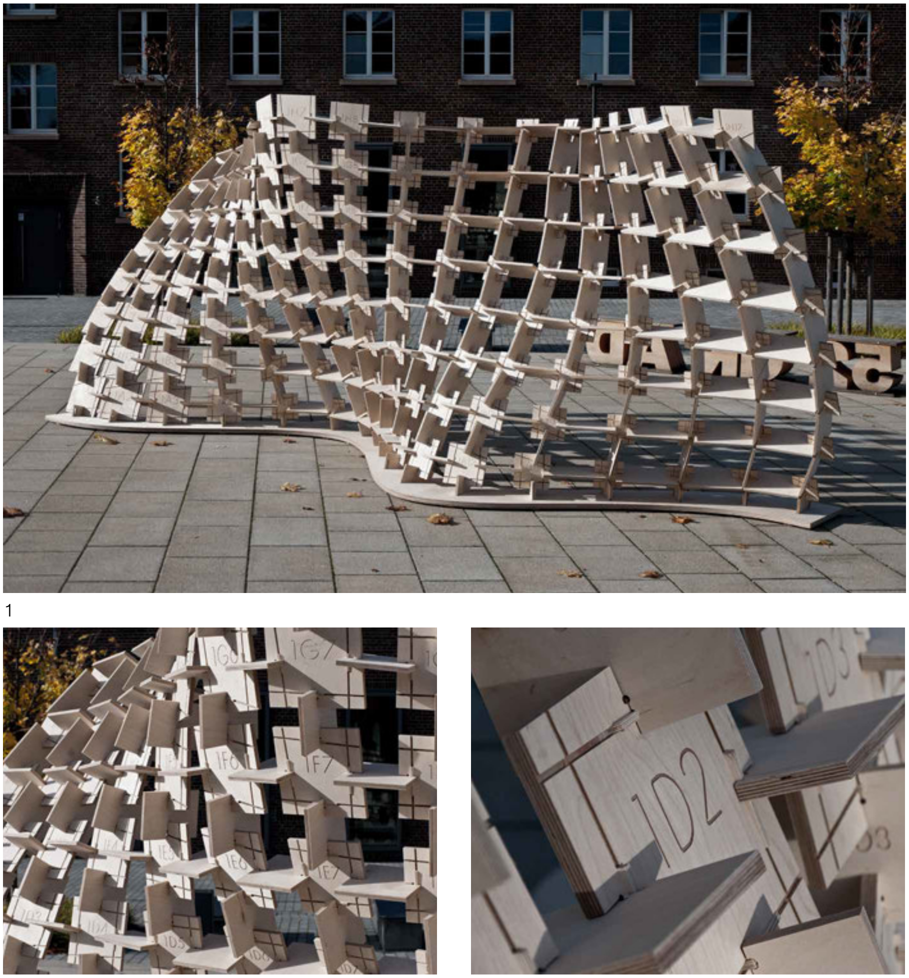

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FIG. 1.7 Realised prototype of the SunSys project

As demonstrated by the parametric workflow in the SunSys project, the previously object-oriented approach, which concentrates on creating a specific design result, is shifted to a system-oriented strategy, which focusses on the process. In this understanding, Terzidis (2006) claims: ‘Digital is a process, not a product.’ However, the application of such processes must be assessed against the architectural results achieved. With the development of pattern language, Christopher Alexander is regarded as a pioneer in system oriented architecture (Alexander, Ishikawa, & Silverstein, 1977). In an interview with Rem Koolhaas and Hans Ulrich Obrist, he takes a critical view of an unreflected use of the computer as a design generator.

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From his point of view, differentiation is important and the design result needs meaning in the sense of the project being worked on (Alexander, Koolhaas, & Obrist, 2008). The necessary reflection clarifies the relevance of the architect as a human part of a design oriented human-computer interaction, as also identified by Menges and Ahlquist (2011).

Today, the influence of parametric design on architecture is evident in a new formal building design. Schumacher (2009) sees this as a new architectural style for which he coined the term ‘Parametricism’. The question of whether parametric design can be determined by the expression of the design result or by the design method is part of an ongoing debate, which is yet to be resolved. Monedero (2000) criticizes that the notion of parametric design does not consider the core aspect of establishing relationships in the design process. Therefore, Trummer (2011) emphasizes the use of the term associative design. The notion underlines the relevance of the computer in the design process as a medium for establishing relationships and for the exchange of information.

Following this way of thinking, parametric models are also an important aspect of Building Information Modeling (BIM). In it, the digital representation of the building forms the basis for collaboration between the stakeholders of the construction process throughout all building phases, from early design stage to the building operation. Bähre (2018) defines BIM as a planning method that enables the entire building life cycle to be taken into account by storing, managing and providing all data in a 3D model. The adaptation of existing planning methods to the strategy of building information modeling represents a current transformation of the building sector, in which different forms are distinguished depending on the scope of the implementation. Little BIM designates the application within a company involved in the planning process, while Big BIM is used across all trades. Depending on whether the planning is bound to a specific software solution or to exchange formats like the IFC standard, software-independent, this is referred to as closed or open BIM. Beyond planning and construction, the 3D model in building information modeling provides the basis for the operating building services, maintenance and renovation as well as the later deconstruction of the building in the form of a digital twin.
A requirement for making use of the digital twin is continuous maintenance and updating of the digital data (Building Information Modeling, 2018).

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SIDE NOTE: **CONFERENCE FAÇADE 2015 - COMPUTATIONAL OPTIMISATION**

facade2015

Nov. 27th // COMPUTATIONAL OPTIMISATION

In the last few decades, information technology has brought about lasting changes to design and production processes. At the same time, our demands on design and building processes have increased in line with technical possibilities. Aside from unprecedented geometrical freedom, there is huge potential to optimize functions, energy and performance of constructions, buildings and services.

Buzz words like Big Data, Industry 4.0 and The Internet of Things already point towards the next Digital Revolution. So what does this mean for building envelopes and their planning and building processes? How can an ever increasing network of information contribute to an optimization of today's designs and constructions?

These issues will be addressed at the conference facade2015 which will follow the same sequence, as the main phases of building development: planning, construction and operation. The potential, chances and risks of progressive digitalization with respect to the the building envelope will be at the center of conference discussions.

8.30 **Registration**
9.00 **Welcoming & Introduction**
Uta Pottgiesser, HS-OWL, Dean
Jens Böke, HS-OWL

Design
9.15 **Digital tools**
Martina Bauer, Barkow Leibinger; Berlin
10.00 **A comforting talk**
Uli Horner & Jeroen Janssen, AKT II Envelopes; London
10.30 **Beyond the skin**
Anthony Chen, Gehry Technologies; Hongkong

11.00 **Coffee break**

Fabrication
11.45 **It's all prototypes**
Hans Sachs, HS-OWL; Detmold
12.30 **File to factory: parametric façades**
Patric Günther, Schüco International KG; Bielefeld
13.00 **Parametric design and engineering**
Paul Rouwen Denz, Priedemann Fassadenberatung GmbH; Berlin

13.30 **Lunch break**

In use
14.30 **Adaptive building envelopes**
Susanne Gosztonyi, Lund university; Lund
15.15 **ThinkingSkins**
Christian Moellering, RWTH Aachen; Aachen
15.45 **Final Discussion**

Registration: **www.werkstatt-emilie.de/weiterbildung/anmeldung**
anmeldung@werkstatt-emilie.de, deadline 11. November 2015
Changes or cancellation are subject to alterations by the organiser

Fees: 150 €
100 € members german chamber of architecture
80 € members Hochschule OWL / members EFN
25 € students / graduates of Hochschule OWL

Venue: Casino, Campus Emilie, Emilienstraße 45, 32756 Detmold, Germany
www.hs-owl.de/fb1/service/anfahrt-kontakt.html

Homepage: http://www.hs-owl.de/fb1/forschung/construction-lab/veranstaltungen/facade2015.html

Hochschule Ostwestfalen-Lippe
University of Applied Sciences
Detmolder Schule für Architektur und Innenarchitektur

HOCHSCHULE LUZERN

Conference poster façade 2015

The *Thinkingskin*s research project was developed in view of a continuous debate on computational strategies in architecture. An exemplary event for this discourse is the conference ‘facade 2015’. The topic of the façade conference at Ostwestfalen-Lippe University of Applied Sciences in Detmold arose from the context of both postgraduate Master’s programmes International Façade Design and Construction (IFDC) and Master of Computational Design and Construction (M-CDC) as well as from the examination of architecture-related computation in the research project *ThinkingSkin*s. As coordinator of the research department ConstructionLab, Jens Böke organised and hosted the event together with a team of professors, research associates and students. The conference took place on November 27, 2015 as part of a façade week and was accompanied by other events such as workshops and network meetings. In line with the title, a focus of the event lay on optimization possibilities resulting from the application of computation to the building sector. The lectures were divided into the three programme sections design, production and building operation according to their respective focus. Against the background of a digitalisation of the construction sector, the conference aimed to obtain a comprehensive overview of the effects of digital strategies on all project phases and to discuss the associated potentials, risks and challenges.

1.3.2 Dynamic and responsive architecture

Despite existing digital design methods, representing dynamic processes as described in Section 1.3.1, the realisation often leads to static results. Buildings are therefore primarily associated with immovable constructions. This becomes particularly apparent in the German term for structural design: ‘Statik’ refers to the load-bearing behaviour of dormant structures. The word is derived from the Greek ‘statikos’ – to bring something to a standstill (‘Statik,’ n.d.). An architecture that allows movement is called dynamic. The term can be misleading because it is also used for buildings that are immovable but appear visually dynamic due to their formal expression (Elkhateeb, Fikry, & Mansour, 2018). This concerns an illusion of movement that does not actually take place. Buildings like the Heydar Aliyev Center with its fluid shape designed by Zaha Hadid architects or the Guggenheim museum by Frank Gehry in Bilbao as shown in FIG. 1.8 can be considered examples for this static representation of dynamic architecture.

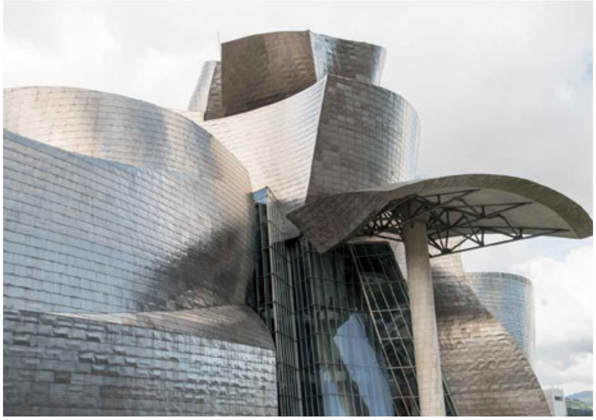

FIG. 1.8 Guggenheim museum in Bilbao by Frank Gehry

The origins of today’s conception of dynamic architecture with actually movable components, such as the example of the Milwaukee art museum by Santiago Calatrava in FIG. 1.9, date back to the 1960s. Norbert Wiener (1961) established cybernetics as the ‘science of control and communication, in the animal and the machine’, which had a decisive influence on the development history of dynamic architecture. Three years later, in 1964, Ron Herron, a member of the Archigram group, formulated an early and radical utopia of a dynamic architecture with his project ‘Walking City’, in which mobile, robot-like buildings form flexible cities. Designed by Greene, also a member of the Archigram Group, these ‘Living pods’ illustrate the building as an active machine (Kolarevic, 2015). Gordon Pask was a British cyberneticist. While cybernetics initially represented a general theory without direct reference to architecture, Pask (1969) established this relationship in his article 'The architectural relevance of cyberneics'. The design concept called Fun Palace evolved from his collaboration with British architect Cedric Price and the theatre director Joan Littlewood. It is considered the first concept of a highly dynamic, cybernetic building. Designed as a concept for a theatre, the Fun Palace was intended to serve various alternative usage profiles by continuous adaptations. It provided interaction with people and a social control system, upon which future adaptations of the building should be agreed (Mathews, 2005). The development of such concepts required a certain understanding of buildings that, according to Pask (1969), went beyond 'pure' architecture. Le Corbusier coined the prominent sentence 'A house is a machine for living in' which referred to his perception of a required standardization of the building sector according to other industries at that time (Le Corbusier, Cohen, & Goodman, 2007). A machine fulfils functions and serves as a building for the human being. In this understanding the building represents a system and requires a corresponding system-oriented way of thinking in the design.

FIG. 1.9 Milwaukee art museum by Santiago Calatrava. From '*Wikimedia Commons*' by Michael Hicks (Mulad) 2006 (https://upload.wikimedia.org/wikipedia/commons/7/79/Milwaukee_Art_Museum_1_%28Mulad%29.jpg) Licensed under CC BY 2.0

The Fun Palace project was not realized but still serves as a conceptual model for contemporary dynamic architecture. Today, the technical requirements exist for the realization of complicated movable constructions that allow adaptations in the building structure. Schumacher, Schaeffer, and Vogt (2009) provide an overview of such possible kinetic constructions which can be realized on all scales.

FIG. 1.10 Heliotrope in Freiburg by © Rolf Disch SolarArchitektur. From *'Rolf Disch SolarArchitektur'*, 1995 (http://www.rolfdisch.de/media-de/bildarchiv/#heliotrop). Licensed under regular copyright. Reprinted with permission

A range exists within the scope of implemented dynamics. Only a few project examples provide the fully dynamic implementation formulated by Elkhateeb et al. (2018) in which the building can adapt or move as an overall system. One example of such a fully dynamic building is the Heliotrope in Freiburg, which can be adapted to the position of the sun by rotation (FIG. 1.10).

Often individual features or components of a building are dynamically implemented, while the main structure remains immobile. In these cases, Elkhateeb et al. (2018) refer to a partially dynamic architecture. Since the façade is a part of the building, its dynamic implementation can be assigned to this category. An example is the Kiefer Technic Showroom by Ernst Giselbrecht + Partner in Bad Gleichenberg, Austria, as shown in FIG. 1.11.

FIG. 1.11 Kiefer Technic Showroom. From '*Graz UNESCO City of Design*' by © paul ott photografiert, 2007 (https://www.graz-cityofdesign.at/images_dynam/image_zoomed/paul-ott_detail02.jpg). Licensed under regular copyright. Reprinted with permission

Two principal strategies in the implementation of dynamics and adaptations can be observed. On the one hand, adaptive structures are made possible by the integration of smart materials (Ritter, 2007). Such materials change their properties dynamically, for example via chemical or biological processes, and enable adaptations in response to external influences, also called 'stimuli'. Since these adaptations are material-integrated, there is no need for a complex mechanical system that incorporates actuators and controls into the design. Kretzer and Hovestadt (2014) formulate the natural appearance of adaptation processes carried out by smart materials as a result of unpredictable deviations that often convey an organic character. The second implementation strategy consists of mechanically performed adaptations. They are carried out on the basis of kinetic structures and respective components, computer-based controls, sensors and actuators. The integration of kinetics as well as automation related devices often leads to complicated systems. In this context, Kolarevic (2015) is committed to the simplicity of possible solutions that should not be ignored by concentrating only on the latest available technologies. A comparison of both strategies reveals that while smart materials offer advantages in simplicity, they are also limited to the predetermined capabilities of the material, while automated adaptations are more complicated and thus more susceptible to errors, but on the other hand allow freedom in programming behaviours and interaction between adaptations. According to Senagala (2006) it is important to differentiate the terms complicated and complex, because despite of their similarity they have a different meaning. A system is complicated due to the amount and hierarchy of integrated subsystems. But it can be assessed as a whole by understanding the individual parts. This is not possible in complex systems, which Senagala (2006) also refers to as ‘non-linear systems’ and ‘living systems’, because complexity addresses dynamic relationships and adaptive behaviour and also incorporates self-awareness. Movement and adaptation lead to the consideration of time as an important new dimension in dynamic architecture. Thus Kolarevic (2015) claims ‘Architecture of Change = Architecture of Time’. Sobek and Teuffel (2001) classify short-term adaptations as processes that are initiated as a direct reaction to an external influence. Systems capable of such direct reactions are designated as responsive (Meagher, 2015). Long-term adaptations take place in the sense of complex systems via growth or evolutionary processes. Kretzer and Hovestadt (2014) see adaptability not in extensive automation and control, but in the ability of the system to interact and learn, and in the fact that it can alter and mature.

Senagala (2006) generally criticizes that dynamic buildings are developed with the primary focus lying on technologies and not on humans. A distinction in the implementation of dynamic architecture lies in the motivation, which according to Moloney (2011) can be divided into two categories. On the one hand, it is about staging the building and about the visual communication with people. Bullivant (2006) identifies this motivation as ‘phenomenological’, resulting from the human fascination for new technologies and the desired experience of interactions with the environment. On the other hand, a motivation lies in the desired effects of the building performance. In this context, Schumacher et al. (2009) distinguish between analogue and digital motion in architecture, depending on whether the focus of an adaptation process lies on the motion sequence itself or on achieving a new configuration. The digital classification of a movement is based on the idea of configurations in the sense of binary states which neglect the required movement processes. Cudzik, Nyka, and Iop (2017) see a current trend in construction projects which, in complicated execution, only serve the external appearance of the building and represent a strive for reactive qualities themselves. Against this background, Fortmeyer and Linn (2014) dissociate from the aforementioned Archigram Group and its idea of a dynamic architecture with a focus on movement itself. They recognize the façade as a central aspect in the consideration of dynamic architecture and emphasize the relevance of a pursued increase in the building performance and in the indoor comfort provided.

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1.3.3 Façades

The façade defines the shape and appearance, but also determines the energy efficiency, the user comfort and the functionality provided by the building. With the aim of providing a constant and comfortable indoor climate, the design of façades and the use of materials traditionally depends on the building's surrounding climatic conditions, next to the user demands. Therefore, the purpose of the façade design varies depending on the geographical location. While in hot regions the focus lies on exploiting cooling effects, in moderate temperatures it is more on balancing seasonal differences or in cold regions on protection against cold temperatures (Sandak, Sandak, Brzezicki, & Kutnar, 2019).

The history of façade development is characterised by the application of technological achievements in response to formulated requirements. This is already evident in the origins of the façade, which, according to Knaack, Klein, Bilow, & Auer (2014) lies both in solid walls, which were intended to offer settled residents durable protection from the weather, and in tent constructions, which offered an advantage in mobility and flexibility (Sandak et al., 2019). The choice of construction represents a response to the living conditions of the inhabitants. Schittich, Staib, Balkow, Schuler, & Sobek (1998) describe the external walls of traditional houses as individual solutions, which provide a high degree of functionality by being tailored to local conditions and available materials and techniques. For a long time, the façade was not recognised as an independent element of the building. As massive wall constructions, it fulfilled the elementary functions of providing protection and insulation, while at the same time being part of the fundamental load-bearing structure. A development step was the creation of complementary façades, in which the functions are distributed over different shells and layers, in the further developments leading towards the dissolution of physical functions from the building's load-bearing structure in curtain walls (Deplazes, 2013).

The predecessor of the use of glass in architecture were palm houses. One example is the Palm House at the Royal Botanical Garden Kew in London. FIG. 1.12 shows the Palm House in Vienna, which is similar in design with its iron and glass construction (Schittich et al., 1998). Modernism gave rise to the expectation of transparent and translucent architecture that meets the new demands of aesthetics as well as the themes of daylight illumination and visual connections between inside and outside (FIG. 1.13). The following large-scale glazing of façades fulfilled these requirements, but also introduced new building physical problems, such as excessive solar gains in summer and unwanted heat losses in winter. Besides the development of new constructive solutions such as double façades, this critical window to wall ratio, as also identified by Favoino, Goia, Perino, and Serra (2016), led to an increasing mechanisation of the building, resulting from the idea that the energetic disadvantages of the glass façade can be compensated with technology. In the course of expanding the functional scope of façades and the additional integration of technologies and building services, the complexity of façades increase. Klein (2013) identifies a multitude of functions in a façade function tree.

FIG. 1.12 Palm House Schönbrunn in Vienna

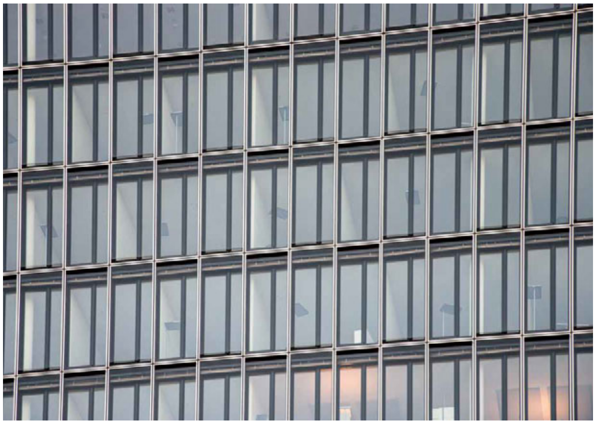

FIG. 1.13 Fully glazed façade of the Kranhaus Süd in Cologne by BRT - Bothe Richter Teherani Architekten

The façade can be interpreted as a system in two ways. On the one hand as an increasingly systematized structure based on standardized components. In this way of thinking, façade systems refer to standardised products provided by façade manufacturers which, due to their standardisation, meet the high building physics requirements of today's façades (Knaack et al., 2014). On the other hand, façades can be understood as systems in the sense of cybernetics and system theory.

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This refers to the combination of different components and elements that are related to each other in the overall system of the façade (Kast & Rosenzweig, 1972). In the second interpretation, the façade can represent an open or closed system. Originally, all buildings were open systems in which it was possible to manually adjust the indoor climate by opening and closing windows or adjusting blinds (Sandak et al., 2019). With the perception of polluted and harmful cities emerging in the 19th century, the objective of a perfect wall emerged that completely isolates the interior from the outside world and guarantees an independent interior climate (Zaera-Polo, Trüby, Koolhaas, & Boom, 2014). At the same time, with the increasing availability of technical possibilities in the field of Heating, Ventilation and Air Conditioning (HVAC), the idea arose that a self-sufficient interior climate could be manufactured mechanically. According to Addington (2009), this lead to the guiding principle 'Seal tight – ventilate right'. Due to their hermetic sealing of the interior, Sandak et al. (2019) classify respective tight façades as closed systems. An example is the Centre Pompidou in Paris. It was designed by architects Richard Rogers and Renzo Piano and was completed in 1977 (Herzog, Krippner, & Lang, 2004). A constant artificial climate had to be created for its use as an art museum. A special feature of the façade concept is the relocation of technical equipment to the outside of the façade, which provides additional freedom for the use of the interior space. As can be seen in FIG. 1.14, the outer appearance of the building is characterised by the assembly of technical elements, such as load-bearing structure, circulation, and ventilation pipes.

FIG. 1.14 Centre Pompidou in Paris by Renzo Piano and Richard Rogers

Adaptive strategies contrast the objective of hermetic isolation. A discussion of both strategies becomes clear in the Hygroscope project shown in FIG. 1.15. This is a responsive sculpture that reacts to changing humidity by means of material properties. The sculpture is presented as a permanent exhibition in the continual interior climate of the Centre Pompidou (Menges, Reichert, & Krieg, 2014). It is housed in a sealed glass box in which the air conditioning is reversed and the humidity of the exterior of the building is mechanically reproduced. The sculpture dynamically adapts to this artificially established exterior climate (Interactive architecture, 2016).

FIG. 1.15 HygroScope: Meteorosensitive Morphology by © ICD Universität Stuttgart. From '*ICD University of Stuttgart*', 2012 (https://www.icd.uni-stuttgart.de/projects/hygroscope-meteorosensitive-morphology/). Licensed under regular copyright. Reprinted with permission

The paradigm shift of adaptive façades lies in the fact that the aim is no longer on working against the climate, but with the climate. Technology again plays a decisive role, but instead of building services engineering it involves components that enable the active role and adaptations of the façade. In most cases, automation technologies applied to façades are part of the broader building automation system. Such systems are organized hierarchically and the composition of the control elements can be represented in an automation pyramid according to FIG. 1.16. There are other representations that show only three levels of the building automation pyramid (Kastner, Neugschwandtner, Soucek, & Newman, 2005). In all models, sensors and actuators belong to the lowest level, which is also called field level. It is here where the interaction of the system with the physical world takes place. The automation level above incorporates direct digital controllers that regulate the automated system. Feedback loops and control logics are subject to this level of the hierarchy, such as possible horizontal information exchange. Control computers represent the upper management level and also enable cross-system functions

(Merz et al., 2009). They have vertical access to all aspects of the system. The development of building automation is manufacturer-driven and various systems and concepts have been developed. There are therefore different technology standards. Examples are BacNet, KNX, Modbus and LonWorks (Domingues, Carreira, Vieira, & Kastner, 2016).

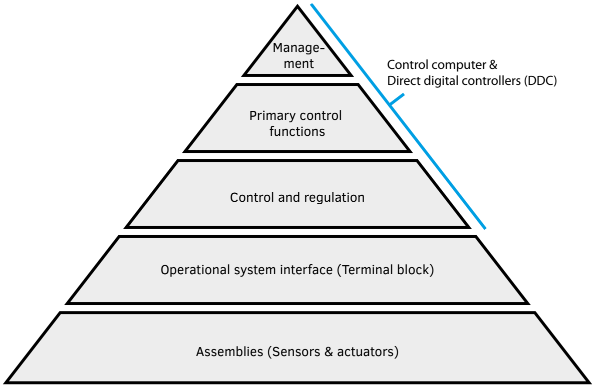

FIG. 1.16 Hierarchical building automation following the concept of an automation pyramid. Adopted from Merz, Hansemann, and Hubner (2009)

FIG. 1.17 shows the façade of the Institute Du Monde Arabe, which was designed by Jean Nouvel and completed 1987 in Paris. The system is equipped with shutters that are able to open and close depending on the sunlight. Herzog et al. (2004) mention the fragility and high maintenance requirements of the system for which it was often criticized. Nevertheless, the project can be seen as a pioneer in using automated building technologies for façades interacting with the environment. The Al Bahr Towers in Abu Dhabi show the technical possibilities available today for extensive façade automation to carry out adaptations. A visible feature are the solar screens, which consist of triangular elements that can open and close gradually (FIG. 1.18). Each of the two towers offers 1049 units, whose organization in the façade system was inspired by a mashrabia. Opening adaptations of the units are carried out by an electric actuator, that is located at the centre of each unit (Karanouh & Kerber, 2015). The project illustrates the active role of adaptive façades and is often cited as an example in this context.

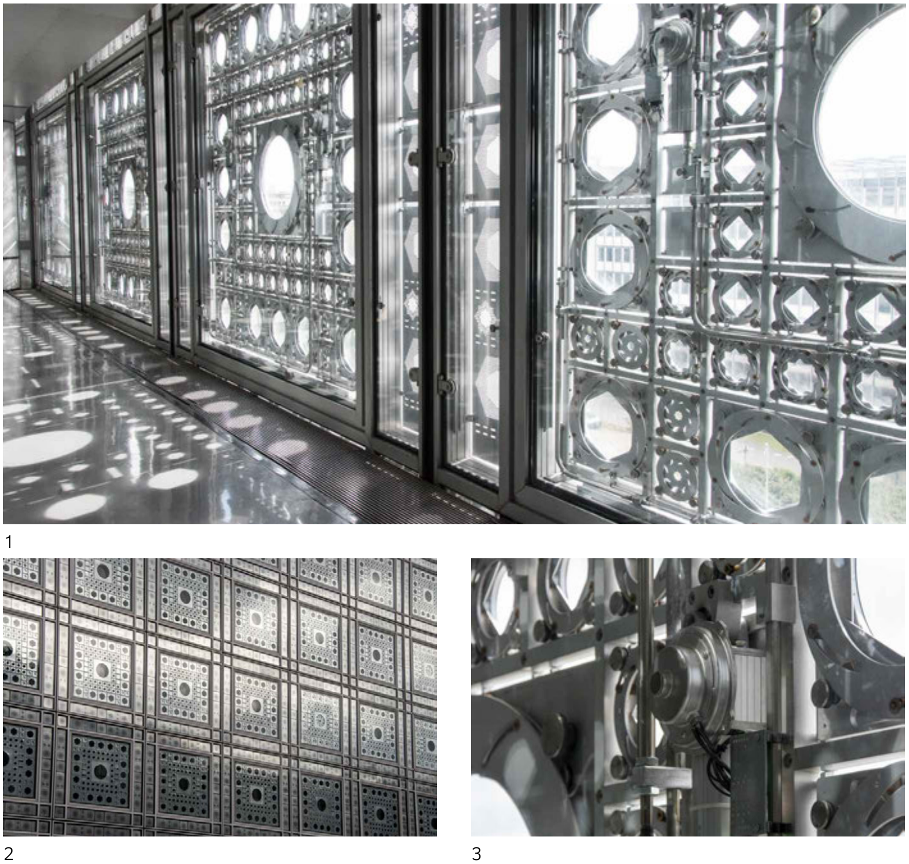

FIG. 1.17 Façade of the Institute Du Monde Arabe in Paris by Jean Nouvel

FIG. 1.18 Responsive façade of the Al Bahr towers in Abu Dhabi by Aedas architects. From ‘*Flickr*’ by © Inhabitat, 2014 (https://www.flickr.com/photos/inhabitat/12330988375/sizes/l/). Licensed under CC BY-NC-ND 2.0

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A globally existing and particularly in Europe formulated objective is to save energy consumption in the building sector ('Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings,' 2010). The façade has a decisive influence on the energy balance of buildings. Today, intensive research is conducted on adaptive systems with the aim of increasing the performance of façades. An example of international efforts in the research of adaptive façades is the COST Action TU1403 – Adaptive Façades (Aelenei et al., 2015). In the field of adaptive façades, existing literature provides a multitude of buzzwords and designations that make it difficult to clearly differentiate the systems. Building envelopes with active capacities are also often termed 'dynamic', 'responsive', 'smart', 'high performance', or 'intelligent' façades. First classifications are provided, for example, by Romano, Aelenei, Aelenei, and Mazzucchelli (2018) and Loonen et al. (2015).

1.3.4 Emerging Technologies

Due to applied artificial intelligence and machine learning, intelligent systems are subject to the ongoing process of digital transformation. In the course of this development a variety of new technologies and strategies emerge. A key aspect is the transformation of the global environment towards an internet of things. The term Internet of Things (IOT) describes the networking of objects, equipped with computing capacities and network ability to form a physical internet. This is possible due to the advancements in information and communication technologies (ICT). Preconditions are the low-cost availability and miniaturization of computer capacities as well as the possible networking via the internet protocol (From machine-to-machine to the Internet of things, 2014). A starting point of the digital transformation can therefore be seen in personal computers and the availability of the internet with the associated World Wide Web since the 1990s (Châlons & Dufft, 2016; Rajkumar, Lee, Sha, & Stankovic, 2010). Since then, various other technologies have been developed that enabled the current wave of digital transformation. In addition to the Internet of Things, Tekic and Koroteev (2019) identify 'artificial intelligence', 'big data analytics', 'cloud computing', and 'social media'.

The internet of things is an aspect of the broader context of cyber-physical systems. The term cyber-physical describes the close integration of physical systems and their digital control, enabled by the embedding of micro-controllers into devices (Wolf, 2012). Cyber-physical systems mean a mutual influence of both domains. Such systems incorporate feedback loops in which the computation on the cyber-level affects the physical system, and at the same time the physical system affects the computations (Lee, 2008). One characteristic is the decentralized organization. In contrast to the previously hierarchical structure of mechatronic systems, cyber-physical systems represent networks of cooperating system constituents. The shift from hierarchical organisation to distributed services is illustrated in FIG. 1.19. In addition to global networking via the internet, corporation can also occur locally, for example in sensitive application areas. Cyber-physical systems are a driver of innovation and, today, are employed in many fields of application. Broy (2010) specifies a number of applications, such as robotics, transportation, medical technology, energy networks, and traffic control. Lee (2008) formulates actual potentials in certain applications, such as in the field of transportation, where an increase in safety can be expected by developing intelligent vehicles or generating energy decentrally that feeds into a power grid. He also recognizes the possible use of cyber-physical systems in building automation, where he identifies the possible increase in energy efficiency through networking HVAC devices and lighting systems. In order to tap the potential of cyber-physical systems, Lee (2008) identifies a requirement for semantic models that enable the interaction between software-based control and physical systems by abstraction. Strategies already exist for the semantic description of cyber-physically designed building automation systems, in which the concept is mapped according to dependencies of the physical structure (Kucera & Pitner, 2016).

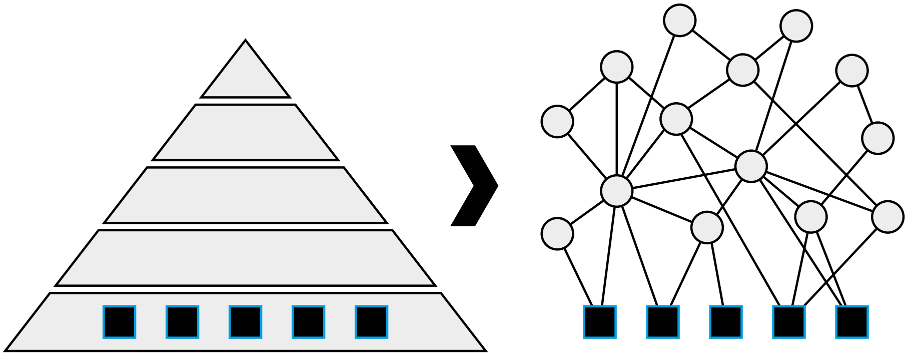

FIG. 1.19 From hierarchical automation to distributed services. Adopted from Monostori et al. (2016)

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A close correlation exists between newly explored technologies and their impact on the economy and society. The research discipline Science, Technology and Society is concerned with these interrelationships, often as a result of politically motivated objectives (Rösing, Price, & International Council for Science Policy, 1977). Digitalisation is a global development that affects all aspects of our life and environment. With an implementation strategy, this transformation process is recognized in Germany as an opportunity for overcoming current societal problems, as well as a challenge in coping with associated transformations and disruptions. In economies, on the one hand digitisation means innovation potential, on the other hand business models have to be comprehensively adapted to the new technologies, which poses challenges especially for large and established companies (Châlons & Dufft, 2016). Data is a raw material of digital transformation, and in the development of the Internet of Things, the number of devices that collect and exchange information is increasing. In this context, classical data mining is exhausted and Big Data represents the strategy for processing large amounts of data. The quality of the data for the respective application is crucial. Therefore filtering raw data leads to tailored, so-called smart data (García-Gil, Luengo, García, & Herrera, 2019). In the OECD report, available data is identified as an input and driver for innovation. Both, the competition between companies that have unique data and their collaboration through the exchange of information play an important role. Digital networks are recognised as platform for knowledge transfer (OECD, 2018).

The application of cyber-physical systems led to a new stage of development in industrial production, which after mechanisation, mass production and mechatronic systems is understood as the fourth industrial revolution, also called Industry 4.0 (FIG. 1.20). The term was coined by the German government in the 'High-Tech Strategy 2020 Action Plan' and has since established itself as a guiding theme (Kagermann, Wahlster, & Helbig, 2013). According to Weyer, Schmitt, Ohmer, and Gorecky (2015), the strategy can be divided into the topics 'smart products', 'smart machines', and 'augmented operators'. Smart products carry information about their processing and become an active member of the manufacturing process by communicating with the production plants. Smart machines address the implementation of cyber-physical production systems (Toro, Barandiaran, & Posada, 2015). Formerly hierarchically organized automation of the manufacturing processes is transferred into decentralized and autonomous production networks. Dumitrescu et al. (2012) describe such networks of production plants as intelligent technical systems that can be characterized by four aspects. Such systems are adaptive and able to interact independently of human intervention. They are robust and can survive unexpected conditions and unpredictable environments. Dumitrescu et al. (2012) also identify the ability to anticipate future conditions based on experience and user-friendliness as characteristics of machine learning. Weyer et al. (2015)

emphasize the modular structure of cyber-physical production systems, in which individual units of the networked system can be removed, replaced or supplemented. Augmented operators refer to the interaction between humans and the cyber-physically implemented production systems.

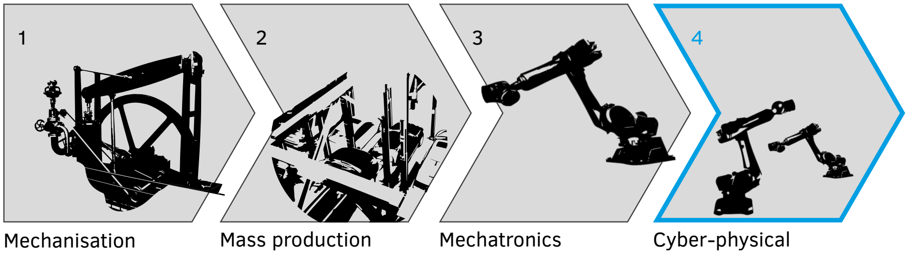

FIG. 1.20 Development stages of industrial revolutions derived from Herwan, Kano, Oleg, Sawada, and Kasashima (2018)

A corresponding networking on the model of the Internet of Things already takes place in the building sector; on a large scale by implementing smart cities and on a small scale by building smart homes. The application of the Internet of Things to communication systems, transport, the education sector and waste management are aspects of the smart city. As a subset, building automation also is an aspect of smart cities (Datta & Sarkar, 2018). The implementation of smart homes is based on embedded and web-enabled devices that are networked locally or via the cloud using a common gateway (Alhammadi et al., 2019). Aims in the implementation of smart homes are described by Bitterman & Shach-Pinsly (2015) as the improvement of quality of life and safety, energy savings, as well as as the support of people with limited abilities and improvements in health care. There is also a commercial drive for the development of smart homes today and many manufacturers of electronic products have recognized this field as a market. Accordingly, there is a wide range of smart products and platforms available today that make their applications possible (Sovacool & Furszyfer Del Rio, 2020).

Capricorn house by Gatermann + Schossig architects in Düsseldorf, Germany

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1.4 Definitions

Certain recurring terminology characterise the subject area investigated. The following relevant terms are defined for being used in the dissertation based on the findings of the background in Section 1.3.

Façade

The structural element that defines the layer between the interior and exterior of a building.

Building skin

Corresponds to the understanding of a façade with additional capabilities of an active mediator role.

Adaptive system

Systems that are able to increase their performance by self-reconfiguration in response to environmental information are regarded as adaptive.

Flexible system

The term is used for systems which have the physical capabilities to be manually adapted. The distinction to adaptive systems lies in the missing autonomy. This understanding corresponds to the required distinction between adaptive and adaptable as identified in Chapter 2 identified. The alternative term flexibility was chosen because of the proximity between both expressions and the associated risk of confusion.

Performance

The term is used both in the understanding of the overall building performance, and more specifically in relation to the façade. The term refers to the effectiveness of the construction, which results from the ratio of the energy invested to the comfort requirements fulfilled.

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Embedded system

Embedding means the equipment of physical objects, technical installations and products with independent processing capacities, for example through the integration of micro-controllers and computers (Wolf, 2012).

Cyber-space

Is understood in the project as a computer-generated virtual space.

Cyber-physical system (CPS)

A system based on the close interaction of physical devices and their digital control is understood as cyber-physical. Due to dissimilar interpretations in different fields of application, against clear definitions, cyber-physical systems are classified by the assignment of fulfilled criteria. In the present research, this includes the embedding of individual system components, their decentralized organization, sensor-based acquisition of environmental data, system-internal communication, and the system monitoring.

Internet of Things (IOT)

The Internet of Things is an application form of cyber-physical systems. It refers to the digital networking of physical objects in general and without reference to a specific application. A technical requirement is the embedding of the objects as described above.

Industry 4.0

The term stands for the fourth industrial revolution, which, in addition to other aspects is based in particular on the application of cyber-physical systems to industrial manufacturing processes.

Intelligent technical system (ITS)

Intelligent technical system refers to the application of cyber-physical systems to networked and cooperating production facilities in Industry 4.0.

1.5 Problem Statement and Hypothesis

1.5.1 Main problem

In computational design strategies as described in Section 6.3.1, the computer enables negotiability of information towards a correspondingly optimal design result. The digital model dynamically reacts in a complex way to changing input parameters and dependencies. It thus represents a continuous adaptation process to dynamic conditions. The environmental boundary conditions as well as the usage requirements constantly change during the use of buildings. Static buildings do not adapt to these changes. The discrepancy between the dynamic adaptability of digital models and the predominant realization of static buildings thus represents a hitherto largely untapped optimization potential.

Dynamic architecture, on the other hand, allows for varying degrees of movement and possible adjustments of the building fabric during building operation. Existing project examples such as the Al Bahr Towers in Abu Dhabi show the technical possibilities of complex constructions that can react dynamically to environmental conditions. In many existing projects of dynamic architecture, extensive use of automation technology in the construction serves the staging of the building and makes no, or only a slight contribution to its energetic efficiency. Thus, great technical effort is expended without affecting the fulfilment of existing building performance requirements.

High demands are placed on the interior comfort of buildings. At the same time, it is a declared objective to reduce energy consumptions in the building sector. Due to the façades decisive influence on the comfort provided and on the energy efficiency of buildings, the demand for highly performative constructions is evident. Adaptive façades are subject to current research as they contribute to the energy efficiency of buildings by actively balancing dynamic environmental conditions and changing usage requirements. The façade fulfils many different functions that influence each other. A challenge lies in the conception of holistic systems in which mutually supporting or contradictory adaptations of different façade functions are coordinated. Against this background, there is a lack of strategies to solve the complexity that results from the interplay of adaptive façade functions in the overall façade system.

On the other hand, new strategies in the implementation of automated systems emerge from the ongoing digitalization. One key aspect are cyber-physical systems, in which a close integration of physical devices with their digital control on the cyber-level takes place. Such systems are used in many fields of application and, for instance in the development of Industry 4.0, lead to performance increases in automated manufacturing processes. Although a potential for the performance of automated systems is becoming evident, a possible transfer of cyber-physical systems to the application field of façades has not yet been investigated.

1.5.2 Hypothesis

The research project is based on the hypothesis that, similar to cooperating production plants in Industry 4.0, façades can be realized as cyber-physical systems in which automated adaptive functions work together to achieve common performance goals.

1.5.3 Sub-problems

The main problem of the hitherto unsolved feasibility of façades as cyber-physical systems can be divided into different partial aspects. The following paragraphs formulate specific obstacles in a transfer of the strategy from existing models in Industry 4.0 to the application field of façades.

- Both subject areas, adaptive façades and the current digitalisation are characterised by many unclear and ambiguous buzzwords and terms. It is , for example, unclear what ‘intelligent’ means in relation to a system in the respective field of application and what strategies are associated with it. As there is no uniform understanding for the transfer of concepts, there also is no knowledge base that refers both to the understanding of the predominant terms and to the underlying state-of-the-art of the respective field of application.
- The façade fulfils many functions that are not necessarily all relevant for its cyber-physical implementation. Important requirements are the possible automation and active role of the respective function as well as its relevance for the performance of the building. These aspects are not taken into account in existing listings of façade functions. Therefore, both the identification of relevant functions and the assessability of their adaptive abilities are missing.

- The actual conditions in building practice are unclear. In most cases, buildings are the result of individual planning processes. The information available on realised façade constructions depends on the project and, if available, refers to the façade as an overall construction. There is a lack of knowledge about the implementation of automation on the detailed level of differentiated façade functions. It is not known which functions are often and jointly automated in façades and are therefore particularly promising for cooperation in the cyber-physical system.
- There are many technical prerequisites for the implementation of cyber-physical systems, such as the installation of comprehensive sensors, the embedding of processing capacities or the communication between system components. It is unclear whether these prerequisites can be established in façade systems. So far, there are no reference architectures that can be used as a model for a cyber-physical façade. Therefore, there is a lack of knowledge on how to design and organize an appropriate system.

1.6 Objectives

The following objectives are directly derived from the identified problems. According to the hypothesis formulated in Chapter 1.5, the main objective of the research project is to investigate the feasibility of façades realized as cyber-physical systems and to provide a first conceptual framework.

- One objective lies in establishing a conceptual basis for the transfer of cyber-physical systems as a strategy from networked production in Industry 4.0 to adaptive façades. A systematic examination of terminology used, such as the term intelligence identified in both subject areas, is intended to create an understanding of existing concepts as well as an outline of the underlying state-of-the-art.
- A further objective is the identification of façade functions that can be regarded as relevant for the cyber-physical implementation based on possible automation and adaptation. In addition, the research should enable a systematic evaluation of the degree of automation and adaptability of the functions. For this purpose, a practical tool is to be developed that summarizes both the identified façade functions and the criteria for their evaluation.
- The implementation of cyber-physical systems is based on a necessary automation infrastructure. One objective is the investigation of the current technical basis in building practice. Priorities in the joint implementation of automated and adaptive functions are to be discovered by means of a systematic and detailed breakfown. This is to identify promising façade functions for consideration in cyber-physical façade systems.

- The study finally aims to investigate the technical feasibility of such systems. The goal is to identify whether fundamental characteristics of cyber-physical systems can also be implemented in façades. The objective is to establish a first reference architecture of cyber-physical façades, which includes an investigation into possible cooperation between individual functions.

1.7 Research question

1.7.1 Main question

The following research question focuses on the conception and feasibility of cyber-physical systems in the application field of façades. It is to be answered in the scope of the research work:

- **How can cyber-physical systems be applied to façades, in order to enable coordinated adaptations of networked individual façade functions?**

1.7.2 Sub-questions

To find an answer to the main question, different partial aspects need to be clarified. In line with the different stated objectives, the following four sub-questions address the individual investigations that are to be carried out in the examination of the research question:

- What are existing definitions and key aspects in intelligent façades and in intelligent technical systems?
- Which façade functions can be identified as possible parts of an intelligently networked façade system and which criteria can be used to evaluate their adaptability within such a system?
- How and to what extent is automation applied to façades and which façade functions are taken into account?
- Is the construction of cyber-physical façade systems technically possible and how can such systems be designed?

1.8 Methodology and structure of the research

The sub-questions are the starting point for the conduction of individual partial studies carried out in the project. There are a total of four separate investigations, each of which constitutes a chapter of this book. The studies build on one another in the development process of the research conducted. Decisions for the choice and type of a subsequent study are based on the results and findings of the previous examination. Correlations between the individual investigations are explained in short transitions between the chapters. FIG. 1.21 illustrates the organisation of the research project with its individual studies. All chapters include independent materials and methods sections, which describe the procedure in the respective study in detail. The following is a summarized overview of the methodology in the overall context.

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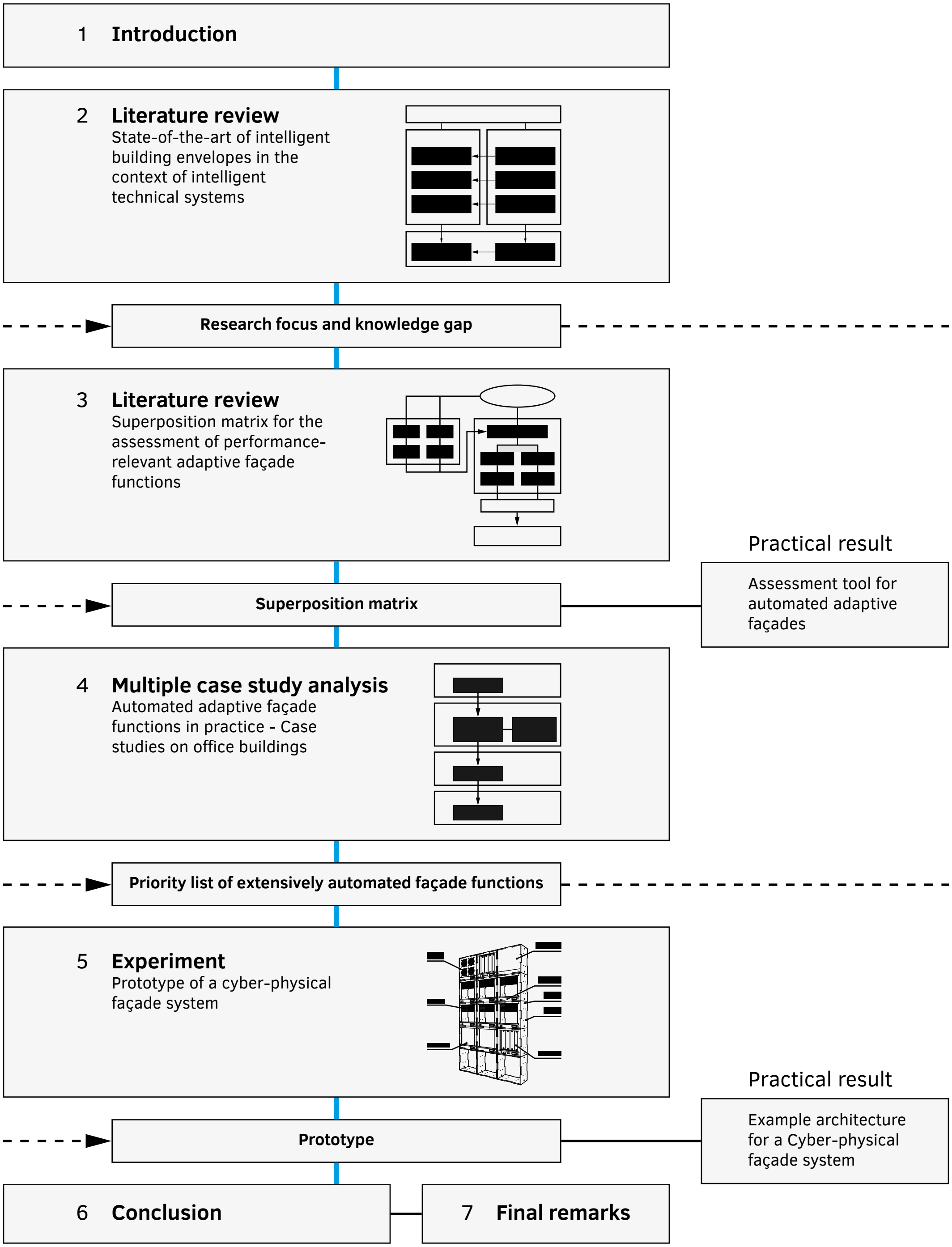


FIG. 1.21 Methodology diagram

In the first investigation, a literature review is carried out to clarify the understanding and the state-of-the-art in the development of intelligent façades. The industry has a leading role in the implementation of current intelligent systems, visible by its guideline of an Industry 4.0 (BITKOM, VDMA, ZVEI: Umsetzungsstrategie Industrie 4.0, 2015). Therefore, the review is carried out in comparison with this application field. The term ‘Intelligent Technical Systems’ has been identified in advance as a keyword for the application of cyber-physical systems to smart manufacturing processes in Industry 4.0. Accordingly, the study starts with the first two search terms ‘intelligent façade’ and ‘intelligent technical system’ as the basis for a systematic and independent analysis of both fields. The compilation of keywords identified in the first search results serves as a basis for further literature search iterations. The review focuses on books and journal articles that are identified via different platforms such as Scopus, Web of Science or IEEE Xplore. In a preliminary inquiry, it became clear that many ambiguous terms and definitions are used in the field of intelligent façades as well as in the domain of intelligent systems in the industry. Therefore, identified keywords are recorded during the investigation. In the sequence of different literature search iterations relevant fields of knowledge around intelligent façades and intelligent technical systems are identified. By comparing the search results of both subject areas, the understanding and development stage of intelligent façades is derived, and knowledge gaps are uncovered.

The subsequent, second study is also based on a literature review. It is organised in two general sections: a contextual and a main investigation. To provide an understanding of the façade functions and possible adaptation processes, the first part of this literature review examines the climatic factors that affect the façade as well as the comfort requirements for the interior. The results of this contextual investigation serve as a foundation for the assessment of façade functions in the main investigation. Potentially automated and adaptive functions with an impact on building performance are identified by recording, filtering and consolidating existing compilations of façade functions, such as the Façade function tree by Klein (2013). In the same approach, characteristics for the assessment of the degree of automation and adaptivity of façade functions are examined. Therefore, a second literature search is carried out to determine existing knowledge about evaluation criteria for the degree of automation and adaptivity of façades. The identified results of various research projects are also filtered for possible overlaps. In a final step, the characteristics that initially refer to the façade as an overall system are assigned to the individual façade functions identified. This superposition results in a matrix as a strategic tool for the detailed and systematic evaluation of façades with regard to their automated and adaptively implemented functions.

The superposition matrix serves as an organisational tool for conducting the third investigation. It represents a case study analysis in which realised façade projects are systematically examined for the automated adaptive implementation of their functions. The selection of the projects relies on an internet search, in which especially building and certification platforms are checked for recently realised office buildings. The final selection of projects also depends on available documentation and the accessibility of contact persons and information. In this study, data is collected from three different sources: from project-related literature, from interviews with experts involved in the projects and from field investigations on site. In a single case analysis, the respective projects are first examined independently of each other. The literature is used to build up basic project knowledge. The expert interviews are based on a systematic interview guide which addresses the aspects of the previously developed superposition matrix. All interviews are carried out by telephone calls or in person. The project information is validated and supplemented by an on-site examination of the projects, which is also documented by photos. A comprehensive evaluation of the obtained data takes place in a cross-case analysis. This is done by superimposing and visualizing the data from all projects, from which the existing technical basis and priorities for the implementation of automated adaptive façade functions are derived.

Due to frequent and comprehensive automation, the three functions solar shading, ventilation and heating and cooling are selected as particularly promising for examining the technical feasibility of façades as cyber-physical systems. This occurs in the experimental realisation of a prototype, inspired by the projects presented by El-Khoury, Marcopoulos, Moukheiber, and Adams (2012) in their book 'Make alive - prototypes for responsive architectures'. The structure of the prototype consists of individual wooden frames, which are screwed together to form a complete system. As a module, each frame represents the instance of a façade function. The functions are represented by different automated components, integrated into the modules. Motorized venetian blinds, for example, illustrate adaptive sun shading, while controllable computer fans simulate the function of mechanical ventilation. Essential criteria of a cyber-physical system are demonstrated in the prototype. This includes decentral and modular organization of the façade functions and their embedding, which is achieved with the integration of microcontrollers. Further aspects are the acquisition of system-relevant data using a sensor network and the exchange of information between the modules by a communication protocol. Following the paradigm of cyber-physical production plants in Industry 4.0, a digital twin is implemented to monitor the system (Negri, Fumagalli, & Macchi, 2017). As an exemplary configuration, the prototype outlines a possible system architecture of a cyber-physical façade. The evaluation of the prototype is qualitatively and visually based on whether the previously defined criteria of a cyber-physical system are fulfilled.

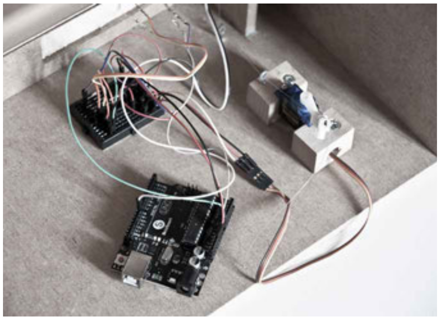
1.9 Article-based development of the dissertation

The doctoral thesis is based on the combination of individual journal articles that complement each other. The four investigations were published in advance by different journal publishers as independent manuscripts. Therefore, each chapter has its own introduction and background relevant to the respective research investigation. All partial investigations share their background in the superordinate research topic of the overall project *ThinkingSkin*s. Despite individual formulations, a certain repetition in the description of the common context cannot be avoided. Therefore, the reader's understanding for possible redundancies in these sections is highly appreciated.

SIDE NOTE: **FIRST IDEA OF A PROTOTYPE**

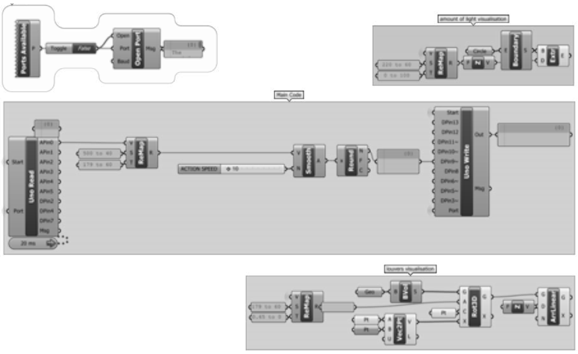
Prototyping was an important aspect of the project from the beginning and led to many insights into the actual implementation of adaptive systems. In the early phase of the *ThinkingSkin*s research project in 2014, Jens Böke developed a forerunner of the later prototype of a cyber-physical façade. Initially, only the two façade functions of sun shading and mechanical ventilation were realised as individual modules. A communication between the functions was not yet considered. In this first approach, the automation was based on an Arduino Uno R3 microcontroller that was programmed with the Firefly extension in Grasshopper 3D. The experiences in the use of electronic components and the Arduino microcontroller platform were decisive for the later implementation of the prototype in Chapter 5 (FIG. A, B, C and D).

A First concept of a solar shading prototype module



B Implementation of automation via a Arduino Uno microcontroller and a servo motor

C Computer fans demonstrate the ventilation system



D Control logic of the automation in Firefly for Grasshopper

Façade of the Oval Offices by Sauerbruch Hutton in Cologne, Germany

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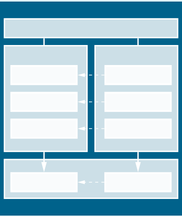
1 Introduction

2 Literature review

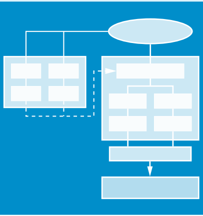
State-of-the-art of intelligent building envelopes in the context of intelligent technical systems



Research focus and knowledge gap

3 Literature review

Superposition matrix for the assessment of performance-relevant adaptive façade functions



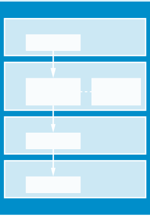
Superposition matrix

Practical result

Assessment tool for automated adaptive façades

4 Multiple case study analysis

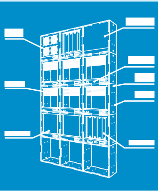
Automated adaptive façade functions in practice - Case studies on office buildings



Priority list of extensively automated façade functions

5 Experiment

Prototype of a cyber-physical façade system



Prototype

Practical result

Example architecture for a Cyber-physical façade system

6 Conclusion

7 Final remarks

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2 State-of-the-art of intelligent building envelopes in the context of intelligent technical systems*

The first investigation serves to establish a knowledge base for the transfer of cyber-physical systems to the façade. Different, existing fields of application of such systems were identified as possible reference models in the exploration of the research background. Industry 4.0 appears particularly promising, as this domain is intensively researched and documented, driven by economic interests. Comparable prerequisites can be found in the implementation of networked production plants, known as intelligent technical systems. This concerns the fixed location of the automated elements, in contrast to cyber-physical systems in transportation and robotics, as well as the technical prerequisites for a basically existing mechatronic automation. In the preliminary probe exploring the background of the research topic, both the existing concept of an intelligent façade and the designation of intelligent technical systems in the development of Industry 4.0 were identified. The assignment of an intelligence represents a common ground of both thematic fields, which are difficult to determine due to the variety of alternative, similar associated terms.
In view of recently emerging technical possibilities in the current digital

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* The chapter is based on a manuscript that was previously published as journal article: Böke, J., Knaack, U., & Hemmerling, M. (2019) State-of-the-art of intelligent building envelopes in the context of intelligent technical systems. *Intelligent Buildings International.* 11(1), 27-45. doi: 10.1080/17508975.2018.1447437

transformation, the question arises whether a comparable understanding of intelligent systems exists in both domains. The understanding of used terms and definitions is accompanied by a state of development of the respective intelligent system. According to the title of the chapter, the state of development of intelligent façades is also examined in the context of intelligent technical systems in current industrial development. The examination therefore also serves to detect a possible deviation from the state of the art in the area of the façade from the state of the art in the Industry 4.0. The following abstract summarizes the research carried out in the first study.

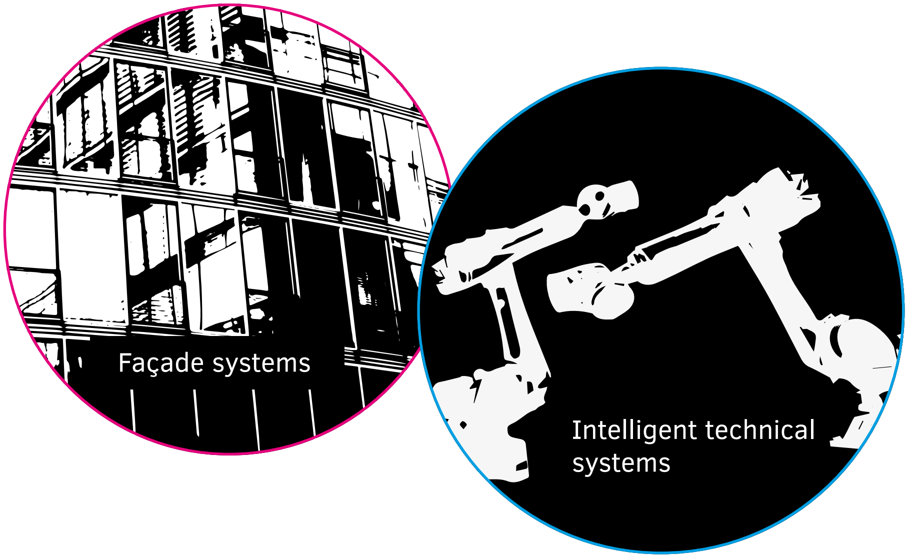

FIG. 2.1 Graphical abstract of the first research investigation

The stringent and increasing requirements concerning energy consumption and the interior comfort of buildings result in a demand for more efficient façade constructions. In its role as a mediator between the exterior and interior of a building, the façade takes on a multitude of functions with effect on the building's performance. Intelligent façades offer higher performances compared to static constructions, achieved by dynamic adjustments to changing environmental influences and interior requirements. Such systems are being explored and already applied. The concept of intelligent façades exists since the beginning of the 1980s. Since then, the technological possibilities for the implementation of intelligent systems have multiplied. Today, the fourth industrial revolution is based on the implementation of intelligent and networked production facilities. Considering the

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current exploration of intelligent technical systems in the industry, the understanding and the demands on the intelligence of a system change. The aim of this study is to examine the comprehension of an intelligent system in the context of the façade and in the context of the industry. This is to provide the basis for subsequent research on the transferability of strategies. The study provides terms used, relevant aspects, current definitions and characteristics of the respective intelligent system.

2.1 Introduction

2.1.1 Background

The façade mediates between the exterior and the interior of a building. In this role, it is faced with continuously changing conditions. These include changing climatic influences from the outside, variable needs depending on occupancy and user preferences inside (Knaack et al., 2014). In its main role as a separation and filter layer, the façade adopts a range of protection, control and regulation functions (Herzog et al., 2004). In the current development, the functional scope of the building envelope is further expanded by the increasing integration of building services (Klein, 2013). The façade has a significant influence on the interior comfort and the energy consumption of the building. We place high and continuously growing demands on both aspects and thus on the performance of the building envelope.

The origin of façade constructions can be seen in massive walls that humans used to protect themselves from cold climates, and in lightweight structures like tents that provided mobility. The understanding of the façade derives from the functional separation of the hull from the buildings structure. The ‘building envelope’ and ‘building shell’ are alternative terms and refer to the façade as such. There are also designations which aim at a special construction principle. In view of an extended functional scope and increasing demands on the building envelope, the development of new technical possibilities has also led to new types of façade construction. The terms ‘curtain wall’ or ‘double-skin façade’ are examples of such specifications (Knaack et al., 2014). For a long time, planners and engineers understood the building envelope as a barrier, with an attempt to shield the interior from the influences of the external space. As an integral part of this concept, building

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services manufactured the interior climate independently of external conditions (Addington, 2009). The performance of a building envelope was measured by how well it protected the interior from the influences of the external environment. This strategy is now extended by the concept of adaptive building envelopes (Favoino, Jin, & Overend, 2014). Adaptive building envelopes respond dynamically to changing conditions and requirements. They utilise climatic changes, and thus reduce the energy consumption for the maintenance of the interior climate of a building. There are a number of realized adaptive building envelopes. Examples such as the Al Bahr tower in Abu Dhabi or the Kiefer Technik Showroom in Bad Gleichenberg usually address individual adaptive functions (Fortmeyer & Linn, 2014; Schumacher et al., 2009). The development and implementation of adaptive façade concepts are in the beginning stages (Aelenei et al., 2015). One challenge is the multi-functionality of the façade. Its features are interdependent and partly mutually exclusive. According to Loonen, the pure addition of individual adaptive features does not automatically lead to an increase in its operability and performance. He states the need for inter-coordinated adaptations that also involve subsystems and building services. The negotiation of individual adaptive façade functions results in the need for an intelligent decision-making in the control of the façade’s adaptations (Loonen, Trcka, Costla, & Hensen, 2013). Within the building industry, the notion of intelligence is not new. The term was used liberally in the past and its understanding has changed with the progressive development of new technologies.

The rapid developments in information and communication technologies (ICT) over the last decade created the technical basis for the current implementation of an Industry 4.0. This refers to the transformation from automated to intelligent manufacturing. After the mechanization, the use of electricity and the application of information technologies, the implementation of cyber-physical systems (CPS) represents the fourth major development step in industrial production (Kagermann et al., 2013). The German government established the term Industry 4.0 by using it in the high-tech strategy 2020 in accordance with the so-called fourth industrial revolution (Oesterreich & Teuteberg, 2016). In addition to the development of smart products and augmented operators, it involves the realization and networking of smart machines (Weyer et al., 2015). These intelligent technical systems are intended to make industrial production faster, more efficient and more flexible, thus ensuring the competitiveness of companies. The building envelope can be understood as a system of its components. The components must co-operate for multi-functional operability of the façade according to the assets in the industrial production chain. It is assumed that strategies and concepts for the control and organization of adaptive façade systems can be derived from industrial intelligent technical systems to the benefit of the building performance.

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2.1.2 Problem statement

The scientific discussion about the understanding of an intelligent façade, but also of an intelligent technical system in the industry is not concluded. It is unclear how the term intelligent is recently defined as it relates to the building envelope, and whether it meets the current understanding of an intelligent system in the industry. In order to be able to draw insights from the implementation of intelligent technical systems for the transmission to the building envelope, a so far non-existent list of preconditions and criteria of such systems is required. At the same time, information is missing about which technical requirements and criteria of an intelligent system the façade already fulfils.

2.1.3 Research question

The main question of this study concerns the understanding of an intelligent system in façade engineering and in the industry.

- **What are existing definitions and key aspects in intelligent façades and in intelligent technical systems?**

The following sub-questions specify the formulation of the main question.

- How are intelligent façades defined?
- Which requirements and subdomains of intelligent façades can be identified?
- What are the criteria for an intelligent façade?
- How are intelligent technical systems defined?
- Which requirements and subdomains of intelligent technical systems can be identified?
- What are the criteria for an intelligent technical system?

The investigation aims to clarify the understanding of the concept of intelligence for the particular topic. It pursues the following objectives:

- To discover existing definitions for intelligence in building industry and in manufacturing industry;
- To identify aspects and criteria for a system being intelligent in both fields;
- To highlight aspects and subtopics for further investigations.

2.2 Methodology

The study is based on a systematic literature review about intelligent façades and intelligent technical systems. Book publications and journal articles were examined. For an initial overview, literature was searched for the terms: ‘Intelligent façades’ and ‘Intelligent systems’. The document titles and keywords were examined. A recognition of this first approach was their systematic composition, consisting of a descriptive property and an application. In a second step, an extended search-term matrix was created based on this organizational principle. It was used for an optimized literature search. The aim of the study is to provide an overview of previous research and definitions in both areas. To avoid detailed papers on particular aspects of the topics, the search terms were complemented with the specifications ‘state-of-the-art’, ‘definition’ and ‘review’. The content-related relevance to the subject and the number of times it has been cited were criteria for the selection of an article. The matrix of search terms is attached as a table in the Supplementary appendix. The results were incorporated into a bibliographic database. Concretized literature searches were performed on individual aspects during the study. Therefore, terms of the search matrix were combined with additional foci, e.g. the term ‘performance’ to find contributions about the efficiency of building envelopes. The combined results of the study are thematically organized (FIG. 2.2).

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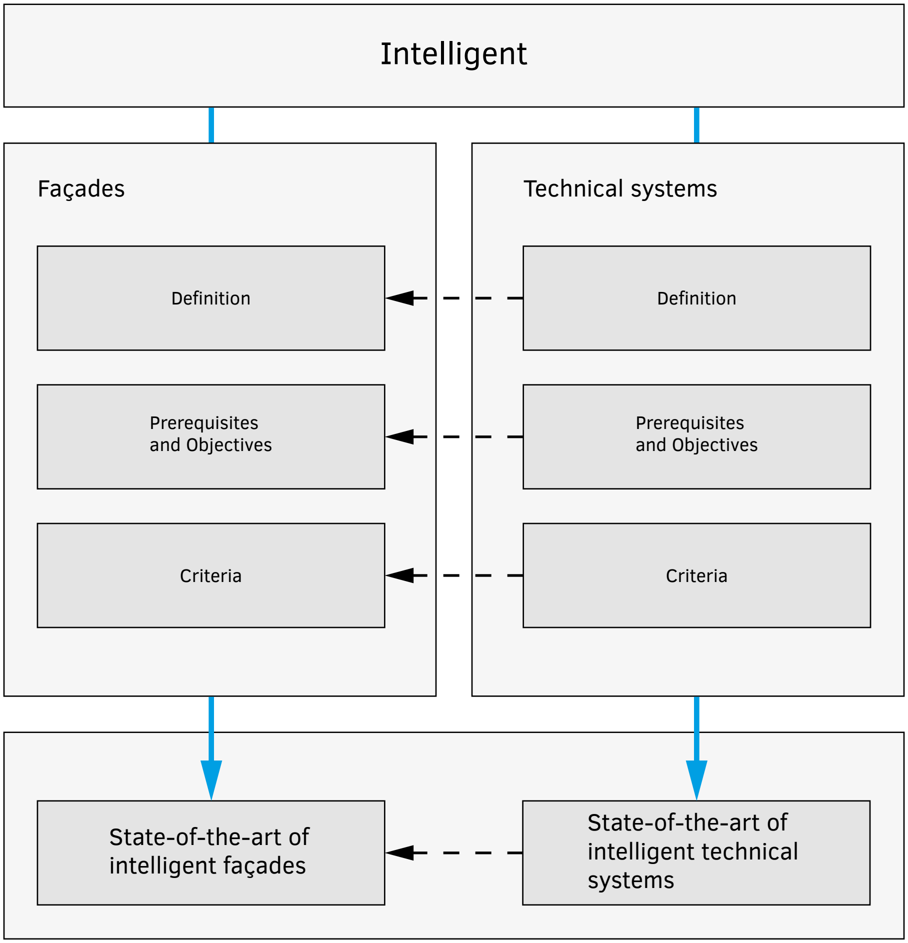

FIG. 2.2 Methodology diagram of the first study: State-of-the-art of intelligent building envelopes in the context of intelligent technical systems

2.3 Intelligent façades

2.3.1 The façade

Regarding intelligent façades, the notion of 'skin' is significant. Origin of this designation is the analogy to the human epidermis. The human skin is understood as a whole without distinction into components such as wall or roof, and it has self-regulating properties (Del Grosso & Basso, 2010; Hausladen, Saldanha, & Liedl, 2008). It recognizes changing conditions or requirements of the body and reacts to them independently. With the term, a similar understanding of the building envelope is associated with respect to the self-regulation between exterior and interior (Wigginton & Harris, 2002) (FIG. 2.3).

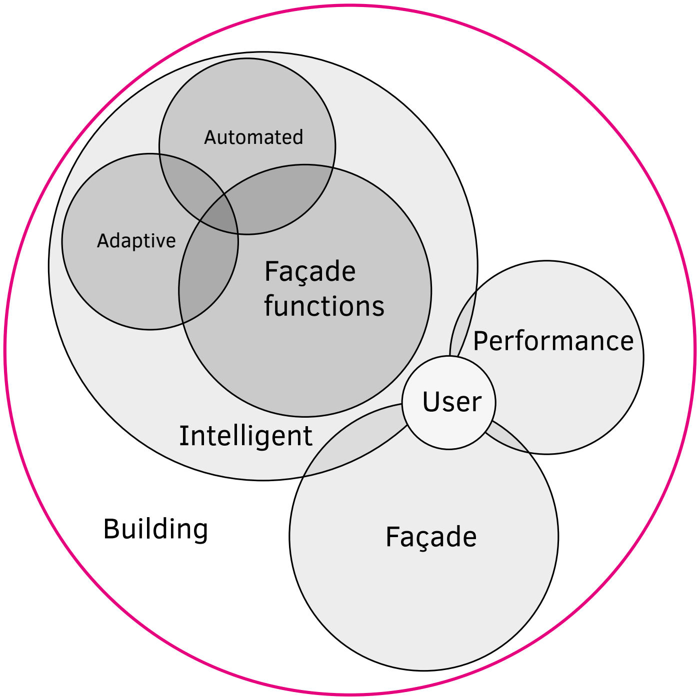

FIG. 2.3 Visualization of the 'Intelligent façades' section context.

2.3.2 The addition intelligent

The term intelligent has its origin in Latin and can be literally understood as ‘to choose between’ (‘intelligent – definition of intelligent in English | Oxford Dictionaries,’ 2017). This generally refers to the ability to make decisions. In the building industry, the addition intelligent led to a series of misunderstandings. According to Wigginton and Harris (2002), there are over 30 definitions for an intelligent building. They state that the term should be used with caution and its meaning should be clarified for the respective context. In principle, two differing interpretations of the addition intelligent are distinguished from each other. Firstly, the term intelligent refers to an intelligent design. It is used in reference to static structures that represent an intelligent solution because of their advanced conception in the design process. Secondly, it refers to structures that provide additional, intelligent features in the building’s operation phase (Wigginton & Harris, 2002).

2.3.3 The context of intelligent buildings

Intelligent façades are a partial aspect in the broader consideration of intelligent buildings. In order to understand the meaning of intelligent façades, the importance of intelligent buildings is clarified first. The concept of the intelligent building emerged in the beginning of the 1980s. Early approaches to define intelligent buildings were primarily based on an extensive technical equipment of the building. Kroner (1997) argues that these buildings were ‘technical enhanced buildings’. Instead of the architecture, the building services became intelligent with little effect on the user comfort. He denounces the practiced separation of architecture, users and intelligent systems. From his point of view, intelligent architecture includes ‘intelligent design’, the ‘appropriate use of intelligent technology’ and also the ‘intelligent use and maintenance’ of the building. In the scientific field, the criticism of the plain technical understanding led to the new interpretation that an intelligent building must involve the user (Wong, Li, & Wang, 2005). In his investigation of the question: ‘what do we mean by intelligent buildings?’ Clements-Croome (1997) comes to the conclusion that it can handle technological and social changes and is adaptable to short- and long-term human needs. The ability to adapt to user requirements and also to changing environmental conditions is an important aspect in today’s understanding of an intelligent building. It must be able to react to individual, organizational or environmental requirements and to deal with changes (Yang & Peng, 2001). Wigginton and Harris (2002) confirm that an intelligent building can adapt to conditions and requirements to create interior comfort with low energy expenditure. They complement the ability to learn. Next to the primary goal of reducing energy costs and providing user comfort, security and automation of maintenance are objectives of the intelligent building (Anshuman, 2005).

2.3.4 Definition of intelligent façades

The ability of adaptation is also a central aspect in existing definitions of the intelligent façade. In this respect, it represents an interface with an arbitrating function (Sala, 1994). The intelligence can be understood as an intrinsic capacity and as the ability to react to circumstances and demands, self-regulating or by means of the user (Kroner, 1997). Compagno (1999) refers the intelligence of the façade to its capability of dynamic adjustments. He dissociates himself from possible definitions over applied technologies and measures the intelligence of a façade by how sustainable it uses natural, renewable energies. Wigginton and Harris (2002) define the intelligent skin as an active and responsive mediator between the outside environment and the interior of a building which ensures an optimal interior comfort with minimal energy consumption. A recent definition describes the intelligent façade as the result of its individual design process, which implements its adaptability with regard to internal and external circumstances. As a result of this process, the façade has components and features that enable the designed adaptation strategies (Capeluto and Ochoa 2017). On the basis of the definitions found, it is clear that the concept of intelligence refers primarily to the adaptability of the façade. Due to possible misinterpretations, researchers and professionals in this field adopted the concept of the adaptive façade (Knaack et al., 2014). Loonen, Trcka, et al. (2013) introduce the term ‘climate-adaptive building shells’ and define it by its ability to adapt continuously and reversibly to changing requirements and influences at least in partial aspects. Adaptations may occur in short-term and long-term periods. Direct reactions to changing conditions are short-term adjustments (Sher, Chronis, & Glynn, 2014). Systems with this ability are often referred to as responsive systems. Long-term adjustments imply advancement processes or an evolution-induced change over generations (Sobek & Teuffel, 2001).

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2.3.5 Automation technology

A façade that allows the changeability of its construction can be regarded as adaptive, even if no automation technology is used and the adjustments have to be initiated by the users (Meagher, 2015). In this context, the designation of adaptability seems to be more appropriate. In many views of an adaptive building envelope, an automated self-regulation of the adaptations is assumed (Macias-Escriva, Haber, del Toro, & Hernandez, 2013). Such a self-adaptive system involves the recording of information, data processing and control, and its transference in adaptations of the construction. Important components are therefore an existing sensing system, which determines relevant information about conditions and requirements depending on the project. Furthermore, a control system processes the recorded information and transmits impulses on their basis to actuators and the actuators themselves perform the adjustments of the construction (Sobek & Teuffel, 2001). Accordingly, (Moloney, 2011) defines the intelligence of a building envelope by the key aspects of an existing 'input system', a 'processing system' and an 'output system'. He complements the 'consideration of time' and the 'ability to learn'. Today, the technical basis for the implementation of self-adaptive constructions exists (Schumacher et al., 2009). In addition to the available sensor and actuator technologies, the research and development of smart materials opens up further technical possibilities (Drossel, Kunze, Bucht, Weisheit, & Pagel, 2015). The control is important as it decides on the behaviour of the self-adaptive façade system. While smart materials refer to an intrinsic control, extrinsic computer-based controls enable real-time optimization and the application of artificial intelligence (Yiannoudes, 2016) Park et al. 2004. Extrinsic control can be centrally or decentrally organized (Loonen, Trcka, et al., 2013). According to whether a feedback evaluation of the system takes place, open-loop and closed-loop controls are differentiated (Sobek & Teuffel, 2001). Evolutionary Algorithms and Artificial Neural Networks are two possibilities of a range of strategies. Evolutionary algorithms simulate generations of possibilities in which the most appropriate solution can be applied. Artificial Neural Networks enable learning abilities. They are based on testing a problem on a reference record. By matching recurring patterns, solutions of comparable problems can be transferred (Sher et al., 2014). In the study of realized intelligent systems in architecture, Yiannoudes (2016) notes that although they can map learning behaviours and respond to user requirements, they work on the basis of previously anticipated rules. As a self-organizing system, the adaptive façade is confronted with complex decision-making between interdependent functions and unpredictable scenarios. Traditional rule-based controls are therefore insufficient in the context of multi-functionality and non-linear adaptations (Jencks, 1997; Loonen, Trcka, et al., 2013).

2.3.6 User orientation

The inclusion of the user is one aspect of the building envelope's intelligence. It is decisive for the acceptance of automated processes whether and to what extent users can interfere with them (Loonen, Trcka, et al., 2013). Research projects investigate the possible interaction between the user and the building envelope (Anshuman, 2005). Also, the user's perception of automated processes plays a role. In investigating the effects of the façade automation on user comfort, Bakker, Hoes-van Oeffelen, Loonen, and Hensen (2014) conclude that adaptions are perceived rather positively if they occur less commonly and restrained.

2.3.7 Alternative designations

In the context of intelligent or adaptive façades, a wider range of terms has been established. Some of them are alternative designations or specify the subject on partial aspects. Many of the terms are not clearly defined (Aelenei, Aelenei, & Vieira, 2016). Researchers demand uniform thought models and vocabulary (Aelenei et al., 2016; Loonen et al., 2015) (Table 2.1).

TABLE 2.1 Alternative designations in the field of intelligent façades

Property	Application
Intelligent	Façade
Smart	Building Envelope
Active	Building Skin
Responsive	Building Shell
High-performance	Curtain Wall
Auto-reactive	Double Skin Façade
Climate adaptive	
Adaptive	
Kinetic	
Dynamic	
Advanced	

2.3.8 Objectives of intelligent façades

An increase in performance can be inferred as the main objective from many of the underlined definitions. The performance describes the degree of fulfilment of a product's relevant functions (Douglas, 1996). The term is used in the understanding of a total building performance, but also with regard to the building envelope and its components. Depending on the scale of the consideration, the performance may refer to material properties, components, elements or the façade as a whole (Hartkopf & Loftness, 1999). One objective of intelligent façades is on the possible energy and the associated cost savings. Traditional evaluation strategies are not effective because of the dynamic properties of adaptive building envelopes (Favoino et al., 2014). Loonen, Favoino, Hensen, and Overend (2017) formulate the potential of building performance simulations in response to the new requirements identified in the consideration of scales, time intervals and physical domains. A further objective is to ensure a constant and high interior comfort. This refers to the satisfaction and well-being of the user. Aspects are, for instance, thermal comfort, air quality and ventilation, acoustics and visibility (Al horr et al., 2016). The goal of intelligent façades is often formulated by combining both aspects, ensuring the highest possible interior comfort while minimizing energy consumption (Compagno, 1999; Wigginton & Harris, 2002). In the consideration of realized intelligent and adaptive building envelopes, the architectural expression and the orchestration of moving components can also be identified as a topic and a goal (*Interactive architecture*, 2016). Active façades, which are exclusively based on aesthetic design goals and do not contribute to the performance of the building, are not covered by the subject of intelligent or adaptive façades (Loonen, Trcka, et al., 2013).

2.3.9 Façade functions

The necessary negotiation of conditional façade functions presents a challenge for the control strategy (Loonen, Trcka, et al., 2013). A comprehensive consideration of the functional scope is required to identify the relevant features of the building envelope in terms of the building performance. There are different approaches to map and to sort the functional spectrum of the façade. According to the definition of Herzog, its main function is separation and filtration between the interior and exterior space. Herzog et al. (2004) divide all therefrom derived requirements into two main groups: site-specific outdoor conditions and demands of use on the inside. He designates control functions as a supplement to the basic protective function of the façade. A comprehensive list of the tasks of a building envelope is summarized in the façade function tree developed by Klein (2013). Not all features have an impact on the interior comfort. The compilation is divided into six overarching categories called primary functions: Create a durable construction, Allow reasonable building methods, Provide a comfortable interior climate, Responsible handling in terms of sustainability, Support use of the building and Spatial formation of façade. Hausladen, de Saldanha, Liedl, and Sager (2005) describe the building envelope as an interface. According to their definition, the functions of the façade are in mutual relation to each other. Meeting the individual requirements can also stand in conflict with the aims of other functions. In his chart, the functions of the building envelope arise as a consequence of the seasonally varying comfort needs of the interior and the basic factors of the external environment. There are other compilations of façade functions that are tailored to specific contexts. Within the research project 'multifunctional plug & play façade (MPPF)', a list of a total of 20 façade functions in the three categories: basic functions, power generation and supply functions was developed (*mppf - The multifunctional plug&play approach in facade technology*, 2015). Also, in the study on adaptive building envelopes, a set of functions was considered as part of its characterization (Loonen et al., 2015).

2.3.10 Criteria and characteristics of intelligent façades

In view of the varied and partly ambiguous definitions of intelligent façades, it is assumed that the examination of criteria and characteristics provides a differentiated overview of its intelligent properties.

Kroner (1997) delivers an early list of criteria (Table 2.2).

TABLE 2.2 List of criteria by Kroner (1997)

Central control	Change of properties	Communication / Media	Change optical properties
Possibility of intervention	Thermo-physical	Video	Patterned glazing
	Thermal resistance	Voice	Remote light control
	Transmittance		Dynamic shading
	Absorptance		
	Permeability		
	Modify color and texture		

In their investigation, Wigginton and Harris (2002) examine realized buildings according to the following features of an intelligent building envelope (Table 2.3).

TABLE 2.3 Criteria by Wigginton and Harris (2002)

The double skin	Learning ability	Temperature controllers	Cooling devices
Building management systems	Sun controllers	Occupant control	Electricity generators
Environmental Data	Ventilation controllers	Daylight controllers	Responsive lighting

Ochoa and Capeluto (2008) provide a list organized according to the existing input and output systems of the adaptive building envelope (Table 2.4).

TABLE 2.4 Criteria by Ochoa and Capeluto (2008)

Class	Category	Design variable	Sub-variable
Input elements	Sensors	No sensors	Illuminance
		Light	
		Temperature	
		Glare / Radiation	
	User interfaces	Switches	
Processing elements	Individual controls	Light controls	
		Shading controls	Type blinds
		Thermal controls	Temperature level policy
		Ventilation controls	Night ventilation
			Active ventilation
		Energy controls	
	Schedules		
	BMS		
	Synchronized controls		
	Passive buildings		
	User only		
Actuating elements	Daylight systems	Sun shading	No / Horizontal / External blinds / curtains
		Daylight redirection	No/ Light shelves / Automatic blinds
	Fenestration	Glazing	Conventional
	Ventilation	Window operator	Fixed / Manual / Mechanical
		Fan ventilation	
	Cooling / Heating	Passive / Active	Orientation / Conventional

Loonen et al. (2015) summarize previously researched character traits of adaptive façades in a matrix with eight categories (Table 2.5).

TABLE 2.5 Characteristics by Loonen et al. (2015)

Objective	Function	Control	Technology
Thermal comfort	Modulate	Intrinsic	Shading
Indoor air quality	Filter	Extrinsic	Insulation
visual performance	Prevent		Switchable glass
acoustic performance	Reject		PCM
Energy generation	Admit		Solar tubes
Control	Redirect		BIPV and solar thermal
	Collect		Shape memory
	Convert		Openings
	Interact		Kinetic systems
			Radiance
Time scale	**Spatial scale**	**visibility**	**Degree of adaptation**
Seconds	Material	No	On-Off
Minutes	Element	Low	Gradual
Hours	Wall	High	
Day-Night	Fenestration		
Seasons	Roof		
Years	Total building		
Decades			

In their comparison, the lists become chronologically more complex. The number of criteria increases from a total of 12 in four categories, identified by Kroner (1997) to 45 criteria in eight categories, designated by Loonen et al. (2015). In particular, individual automation aspects of the building envelope are named, such as Temperature- or Sun controllers in the list by Wigginton and Harris (2002) or, Light- and Shading controls identified by Ochoa and Capeluto (2008). Contrary to their technology-oriented perception, Loonen et al. (2015) focus more on functional aspects such as the objective, function or the type of control. All constellations have in common that they relate primarily to the physical components, the hardware of intelligent façades. Apart from learning ability, there are no software-related criteria, such as the ability to make independent decisions based on existing artificial intelligence, or the degree of networking and communication between the automated components.

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2.4 Intelligent technical systems

2.4.1 Technical systems

Within technical domains, the term technical system replaced different, difficult to distinguish terms, such as ‘plants’, ‘machine’ or ‘device’. The task of technical systems is to transform, store or transport materials, energy or information. Material, energy and information-based technical systems are distinguished. They include a structure and a function. Components that can be separated by an imaginary system boundary from the systems environment constitute the systems structure. The properties and interactions between the components are part of the structure. The function of the system is to transform inputs into appropriate outputs. The total of all transformations inside the system is the ‘process’ (Dumitrescu, Jürgenhake, and Gausemeier 2012) (FIG. 2.4).

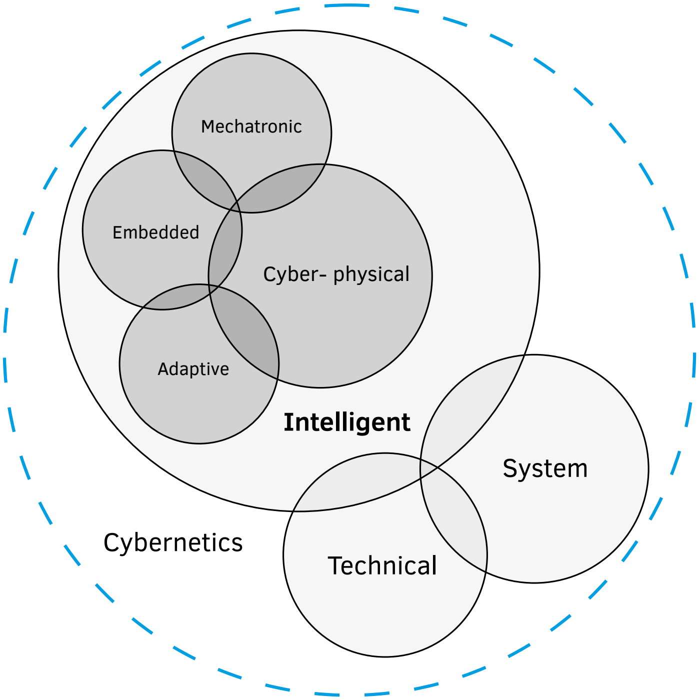

FIG. 2.4 Visualization of the ‘intelligent technical systems’ section contexts

2.4.2 The context of cybernetics

Against the background of comprehensive digitalization, cybernetics provides access to the interaction between human and machine and between machines amongst each other. Norbert Wiener introduced the science of control and communication under the notion of cybernetics in 1948. As a theoretical consideration of a system's behaviour, cybernetics can be applied to different application fields. They support the design of intelligent technical systems (Wiener 2013; Sher, Chronis, and Glynn 2014). A focusing of the topic has resulted in the technical cybernetics (Pickering 2015). The cybernetic system consists of an input and an output record. Interdependent system parts change over time and cause a shift in the overall system. All parts of the system are expected to pursue a uniform goal. Cybernetic systems can be classified into two orders. In the first order, the cybernetic system represents a closed-feedback circuit. The effects of the system are recorded as input values. Negative check-back indications lead to an adaptation of the system. In its first stage, the cybernetic system performs a continuous optimization with respect to a target state. Von Foerster (2003) additionally identifies the observer as an integral part of the system and thus establishes the theory of second-order cybernetic systems. He describes them as a cybernetic consideration of cybernetic systems. They provide the concept model for technical systems with intelligent properties, such as self-organization or communication (Heylighen and Joslyn 2001; Yiannoudes 2016). With reference to architecture, the relevance and transferability of cybernetics is not new. Gordon Pask formulated the demand for cybernetics and identified the interaction between space and users as a closed-feedback loop. An early and often cited example of the application of second-order cybernetic systems in architecture is the project Fun Palace by the British architect Cedric Price (*4dsocial* 2007; Frazer 1993).

2.4.3 The context of mechatronic systems

The term mechatronic was coined in the 1960s in Japan and consists of the two terms mechanics and electronics. Mechatronics refers to the cooperation of mechanical constructions, electronics, control and software. Due to the combination of these aspects, it is an interdisciplinary topic. Mechatronics extends the behaviour and capacities of technical systems by the integration of information. The structure of a mechatronic system is also called its architecture. Mechatronic systems consist of a mechanical structure, the so-called base system. Existing sensor devices receive information about the environment or the system itself. Also, human inputs belong to this aspect of information gathering. The collected information is processed by an ‘information processing system’. The adaptation of the mechanical construction is carried out via actuators. The relationships between the different components of a mechatronic system are defined by flows. There are three types of flows: material, energy and information flows. Several individual mechatronic systems can be merged hierarchically into an overall system (Dumitrescu, Jürgenhake, and Gausemeier 2012; *Design methodology for intelligent technical systems* 2014).

2.4.4 The context of adaptive systems

Changeable systems can be modified after their implementation. Ross, Rhodes, and Hastings (2008) define the changeability as a possible transformation of a system to a new condition within a period of time. They identify the agent as impulse, the change mechanism and the effect of the change as its three constituents. According to Ross, Rhodes, and Hastings (2008), a system is flexible in case of an external agent and adaptable in case of an internal agent. Flexibility and reconfigurability are sub-themes of changeable systems. Ferguson et al. (2008) formulate the demand for such systems as a consequence of the requirements: to be able to fulfil different tasks over a period of time, to be able to be transferred into new configurations and to remain operational despite the failure of individual system components. They define the flexibility of a system as the simplicity of its possible change. According to Olewnik et al. (2004), flexible systems perform real-time adaptations. Their performance is enhanced by their adaptability in predictable environments and they are robust due to unpredictable influences. Adaptive systems are a precursor to intelligent technical systems. Due to applied algorithms, they are able to adapt to changing conditions without user input (Feigh, Dorneich, and Hayes 2012). The limit of such systems lies in the adaptability to requirements of an unpredictable environment (*Design methodology for intelligent technical systems* 2014).

2.4.5 The context of embedded systems

Mechatronic systems with integrated microcomputers are defined as embedded systems. Today about 80% of existing computers are installed in components or products. In most cases, micro-controllers are used as the preferred hardware. Unlike multi-purpose computers, they follow a predefined programme which may be stored on the controller itself. Micro-controllers are differentiated by their computing power. Due to their low-cost availability, 8-bit controllers are often installed, even if their computing power is not very high. For computationally intensive tasks, there are 16-bit or 32-bit micro-controllers. In mechatronic systems, micro-controllers are used for the interaction with the sensors and actuators. Embedded systems are a technical basis for CPS. The implementation of information technology enables intelligent control of individual components, but also their decentralized interlinking towards a networked system (Wolf 2012; Czichos 2015).

2.4.6 Definition of intelligent technical systems

Intelligent technical systems are, in addition to the implementation of intelligent products, a partial aspect of the fourth industrial revolution (Industry 4.0). In accordance with the implementation strategy by the platform Industry 4.0, objectives are increased production efficiency, higher flexibility, implementation of downstream services and the physical and cognitive support of employees (BITKOM, VDMA, and ZVEI 2015). Intelligent products carry the knowledge of their manufacturing process in themselves and independently find their way through a configurable production chain (Brettel et al. 2014). The leading-edge cluster Intelligent Technical Systems (2012) OstWestfalenLippe (it's OWL) introduces the concept of the intelligent technical system. It is based on the combination of different knowledge domains such as information technology, cognitive science or neurobiology. It is a further development of mechatronic systems with regard to its information processing (Dumitrescu, Jürgenhake, and Gausemeier 2012). Cognitive data processing enables the adaptability of the system behaviour and supplements previously rigid controls. Intelligent technical systems are capable of learning and can react flexibly and intelligently to changing requirements and conditions. The learning ability is based on processed information and takes place, according to Dumitrescu, Jürgenhake, and Gausemeier (2012), on the three levels of cognitive, associative and non-cognitive control. Another aspect of intelligent technical systems is their close networking. This is ensured by means of a communication system which allows the exchange of information between intelligent technical systems and their subsystems. The interaction with humans is a significant aspect, manufactured via a human machine interface. The basis for the implementation of intelligent technical systems is created by technological developments such as smaller electronics, the development of new software and methods for handling complexity and the possible virtual networking of information systems. In this context, cyclic-physical systems represent the interlinking of physical systems with the virtual world (Gausemeier et al. 2013; *From machine-to-machine to the Internet of things* 2014; 'Intelligent Technical Systems OstWestfalenLippe - Proceedings of 1st Joint International Symposium on System-integrated Intelligence: New Challenges for Product and Production Engineering - Roman Dumitrescu, Christoph Jürgenhake, Jürgen Gausemeier - Publikationen Heinz Nixdorf Institut').

2.4.7 Cyber-physical systems

Various terms such as Intelligent Technical Systems, ‘Industry 4.0’, ‘Internet of everything’, ‘Internet of Things’, ‘FOG’, ‘System of Systems’ or ‘machine-to-machine’ describe today’s issue of a close combination of the virtual and physical environment. In this context, the general term CPS has prevailed. The prefix ‘cyber’ refers to cybernetics as previously described. The association with the cyberspace often leads to misunderstandings. Wireless networking can be an aspect of CPS but is not a requirement. The term was founded in 2006 in the National Science Foundation in the United States. This refers to the convergence of computer-based components and physical components (plants) in one system. It involves the close interaction between both levels (Lee and Seshia 2015).

Today, the technological requirements for such systems are provided by miniaturized electronics, the development of high-performance software and the possible networking of information systems. Software is an important aspect of CPS. They are also known as ‘software-intensive systems’. Wang, Torngren, and Onori (2015) assume that the software is a major factor of the investment costs for the implementation of CPS. The potential of the software stems from its high flexibility. Any hardware can fulfil various tasks based on different software, which is not material bound, nor subject to technical restrictions. Software can be easily copied and offers great design freedom. Based on the software, various aspects such as computing, communications or the evaluation of information can be negotiated within a system. In practice, the high flexibility of the software requires a strict limitation towards the system’s actual needs (*Cyber-Physical Systems* 2010).

In many sectors such as transport, the manufacturing industry, the building industry or aviation, CPS are currently being researched and applied. Following Wang, Torngren, and Onori (2015), there is a corresponding number of approaches towards a definition. These are either specific and relate to a concrete field of application, or they are too broad for an applicable delimitation of CPS. CPS are, for example, defined as a transferable technology for monitoring networked systems on their computer-based and physical level. Researchers have moved towards the formulation of CPS characteristics for a common comprehension across different platforms. Wang, Torngren, and Onori (2015) identify 10 characteristics of a CPS. These include whether it is an embedded or IT-dominated system, whether it is a single application or cross-platform application, and whether the system is open or closed. Furthermore, it denotes the degree and type of automation, the adaptability of the system and the degree of integration as aspects to consider. Following Wang, Torngren, and Onori (2015), a CPS can also be characterized by the degree of decentralization of its control, as well as by whether there is a human–computer interaction, or if it is completely autonomous. As a final aspect, Wang, Torngren, and Onori (2015) list the degree of vertical and horizontal integration of the system.

Broy characterizes CPS by a direct linking between the physical and the digital environment. From his point of view, the multi-functionality, ensured by functional integration, is as crucial as the exchange of the systems with each other and with their environment. Here, Broy talks about an extensive interaction within and across networks. Moreover, autonomy and adaptability play a role against the background of changing and dynamic operating environments. Following Broy, long-term operations, the functional and access security and the reliability of the systems are additional characteristics. Broy classifies systems according to their degree of crosslinking. He distinguishes five levels, starting with a local, non-crosslinked and mono-functional system. This is followed by multi-functional but non-networked systems, by loosely networked systems and also by networks of functional systems. On top there are systems of systems, such as CPS (*Cyber-Physical Systems* 2010).

In the context of high expectations towards CPS, Monostori (2014) recognizes future challenges in research and development. These include the adaptability and autonomy of the systems, the development of advanced algorithms for the systems cooperation and foresight in continuously changing environments. Moreover, Monostori (2014) identifies the merge of physical systems and virtual systems but also the human–machine interaction as future challenges.

2.4.8 Alternative designations

Starting from the term ‘intelligent technical systems’, further designations are identified that describe the subject field. Many of the terms are composed of an attribute and an application. Names identified as being independent are listed under the category stand-alone terms (Table 2.6).

TABLE 2.6 Alternative designations in relation to intelligent technical systems

Property	Application	Stand-alone term
Intelligent	System	Cybernetics
Smart	Technical System	Technical cybernetics
Cyber-physical	Environment	Internet of Things
Embedded	Machine	Industry 4.0
Cognitive		Things that think
Adaptive		Systems of systems
Self-Adaptive		Internet of everything
Cybernetic		
Mechatronic		
Self-Optimizing		
Adaptronic		
Expert		

Against the background of the extensive and complex subject of intelligent technical systems in the industry, the following lists of criteria are identified as an addition to the definitions found.

Dumitrescu, Jürgenhake, and Gausemeier (2012) describe the characteristics of intelligent technical systems organised into the four categories: adaptability, anticipation, user-friendliness and robustness. They also identify capabilities to which they can be moored (Table 2.7).

TABLE 2.7 Criteria of intelligent technical systems by Dumitrescu, Jürgenhake, and Gausemeier (2012)

Adaptive	Robust	Anticipative	User friendly
Environmental interaction	Flexible	Processing empirical knowledge	Interact sensitively with user
Autonomous	Unpredictable environments	Anticipate future impacts	Adapt to user
Evolve-ability within framework	Overcome Uncertainties	Anticipate possible states	Comprehensible behaviour
Ensure long-term existence	Overcome lack of information		

The following characteristics by Dumitrescu, Jürgenhake, and Gausemeier (2012) refer to the intelligence itself. Some of the aspects, such as the adaptability, interfere with the previous listing. The criteria relate in particular to control capabilities, such as the exchange of information or the ability to learn (Table 2.8).

TABLE 2.8 Criteria of intelligence by Dumitrescu, Jürgenhake, and Gausemeier (2012)

Active	Embedded	Exchange information	
Flexible	Adaptive	Action-control	Information representation
Learning-ability	Anticipative		

Table 2.9 presents a concept map for CPS ('Cyber-Physical Systems - a Concept Map').

TABLE 2.9 Cyber-physical systems concept map

Feedback systems	Cyber Security	Design tools and methodology	
Networked	Resilience	Specification	Hybrid Models
Distributed	Privacy	Modelling	Heterogeneous Models
Adaptive	Malicious Attacks	Analysis	Networking
Predictive	Intrusion Detection		Interoperability
Intelligent			Time synchronization
Real Time		Scalability	Modularity
Human interaction		Complexity Management	Synthesis
			Interfacing
		Validation	Assurance
		Verification	Certification
			Simulation
			Stochastic Models

Lee, Bagheri, and Kao (2015) define a '5C architecture', in line with the automation pyramid, as a framework for the implementation of CPS in the industry. They divide the structure of CPS into five levels. The Connection level corresponds to the field level and comprises the connection to the sensor network. On the Conversion level, data are processed into information. On the cyber level, the exchange with other systems takes place. The Cognition level includes decision support and the monitoring of the system, while the Configuration level includes the 'Resilient control system' (Lee, Bagheri, and Kao 2015) (Table 2.10).

TABLE 2.10 ‘5C architecture’ for cyber-physical systems

Level	Attributes		
Configuration	Self-configure resilience	Self-adjust variation	Self-optimize disturbance
Cognition	Simulation and synthesis	Remote visualization	Collaborative decisions
Cyber	Twin model	Variation identification	Clustering
Conversion	Smart analytics machine health	Smart analytics data correlation	Degradation / Performance prediction
Connection	Plug & Play	Tether-free communication	Sensor network

In consideration of all constellations, the criteria relate primarily to the, for example, networked or distributed compilation of intelligent technical systems, as well as to the abilities of their control, for example, to be able to act in unpredictable environments.

2.5 Discussion and further research

The investigation into the two subject areas provides an independent overview of the understanding and development of a respective intelligent system. In the industry, the application of CPS to production processes leads to a new development stage that has not yet been achieved in the field of adaptive building envelopes. Insights and strategies from the industry can be transferred to the building envelope for an increase in performance of the systems. This refers to the manufacturing processes of a façade industry equipped with intelligent technical systems. Menges (2015) describes such a possible application scenario of CPS in architecture-related manufacturing processes. It is assumed that in addition to an increase in productivity and flexibility, there is a potential in the individualization of façade production, the so-called mass customization (Brettel et al. 2014). On the other hand, an application to the functioning of intelligent façades in building operation is conceivable. Against the background of an increasing automation of the building envelope, a potential is seen in the networking and intelligent control of façade components. It is expected that the application of CPS can contribute to the future viability of multi-functional adaptive façades. The transferability of strategies must be examined in subsequent research for the specific cases.

2.6 Conclusion

Given the found and not uniformly defined terms, it becomes clear that there is an active and unfinished discussion about intelligent systems. The study also shows that there is no complete and general understanding of a system's intelligence in façade engineering and in the industry. The following conclusions are drawn on the specific sub-questions:

Contrary to the expectation that the intelligence of the building envelope refers to its intelligent control, the concept is mainly related to its construction-related adaptability. This recognition is supported in the lists of criteria of an intelligent façade, in which primarily automated components are named instead of capabilities of their control. In the industry, a distinction is made between flexible and adaptive systems with regard to an external or internal agent. This separation has not yet been clearly defined with regard to the façade. The distinction between the term 'adaptable' for constructively adaptable façades and 'adaptive' for those façades that adapt independently on the basis of automation technologies appears necessary. Aspects like artificial intelligence and self-organization were identified in the subject field. In the found definitions, they appear as a sub-range of respective specifications. No specific designation has been found for such façade systems, which can be regarded as intelligent because of intelligent control, for example in the form of a decision process or the mapping of learning behaviours. Such properties have been identified in the industry as crucial to the intelligence of a technical system. In its history of developments, new terms addressed technological improvements of the façade. The term skin represents adaptive features and the ability of self-regulation. A descriptive supplement is missing, which emphasizes cognitive abilities. Such a façade must be able to make decisions on the basis of collected information and in the awareness of existing requirements. Against this background, the concept of a thinking façade would be appropriate.

The study identifies the performance as the main objective and the multi-functionality of the façade as a relevant aspect. Furthermore, the diversity of existing and non-uniform designations is to be noted.

The investigation determines different constellations of characteristics of the intelligent façade. It is crucial how the concept of intelligent façade is interpreted. There are constellations which deal explicitly with characteristics of the ability to adapt. Furthermore, there are lists of the components that are available with regard to an adaptive system, as sensors and actuators. The foundations are hardly

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comparable against the background of different conceptions of an intelligent façade. No characterization has been found which specially focuses on the control strategy and the behaviour such as learning ability or self-organization.

The concept of intelligent technical system reflects the specific application field of intelligent production in the global context CPS. It is characterized by the development of Industry 4.0 in the German economy. The study could not determine a general definition of an intelligent technical system; instead, it provides a description of the development and characterization of the properties and capabilities of such a system. The study shows that the transformation from mechatronic systems to intelligent systems is based on the combination of many fields of knowledge. The use of cognitive controls and the interactive networking between machines with each other and with humans are highlighted as important aspects.

The implementation of intelligent technical systems is based on multiple technological requirements. Against this background, control principles of mechatronic and adaptive systems and the embedding of computer technology into components are identified as important aspects. Cybernetics is recognized as a relevant science because it provides a conceptual framework model for the interaction of machines and people in such a digitized production environment.

The study identifies criteria both in the direct context of intelligent technical systems and in the expanded understanding of CPS. In addition to a mindmap-based set-up, the deployment as an advanced automation pyramid appears as promising to identify capabilities of controlling an intelligent system.

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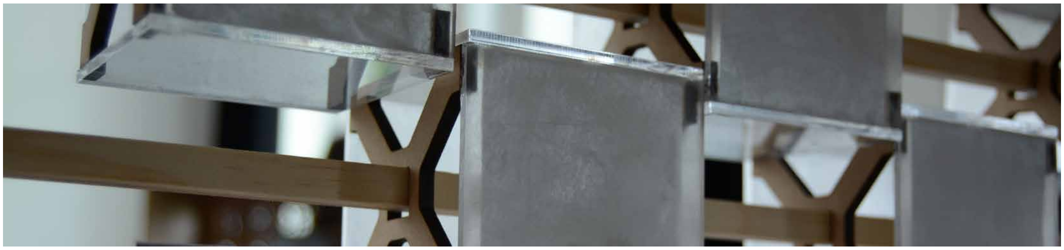
SIDE NOTE: **EFN MOBILE WORKSHOPS IN DELFT UND DETMOLD**

The research project was accompanied by different workshops, which contributed not only background knowledge on individual façade functions but also provided creative ideas for their responsive implementation. Both exemplary workshops ‘ThinkingSkins’ in Delft and ‘Façadetronics’ in Detmold were held by Jens Böke as part of the efn Mobile Program in 2015. FIG. A shows the teaser image of the workshop in Detmold. Together with the Master’s student particpants, concepts for innovative automated and adaptive façade features were developed. The students developed their ideas in interdisciplinary teams based on individual façade functions that were randomly assigned to them. The designs were documented in concept posters and were realized as physical prototypes (FIG. B, C, D, E, and F). The results were finally presented as visible in FIG. G to the group of workshop paricipants and a specialist audience at the conferences ‘Building envelope 2015’ in Delft and ‘Façade 2015’ in Detmold.

A Workshop teaser image

B Physical prototyping

C Two finished prototypes



D Concept for the mechanical adaptation of the visual relations between inside and outside

E Digital design process based on 3D models

F Digital fabrication of the prototypes

G Presentation of the results

Façade of the Post Tower by Murphy & Jahn architects in Bonn, Germany

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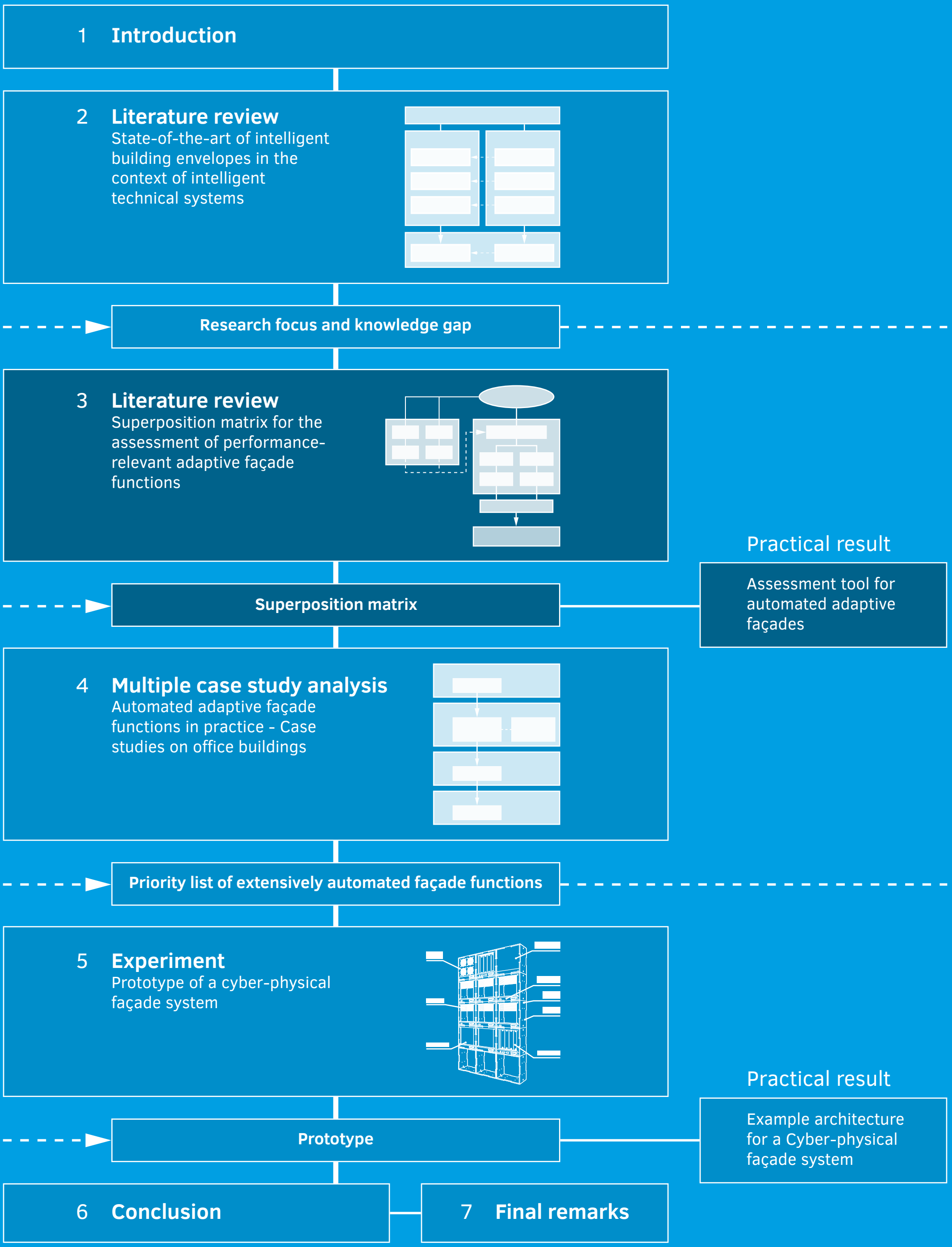

1 **Introduction**

2 **Literature review**
State-of-the-art of intelligent building envelopes in the context of intelligent technical systems

Research focus and knowledge gap

3 **Literature review**
Superposition matrix for the assessment of performance-relevant adaptive façade functions

Superposition matrix

Practical result

Assessment tool for automated adaptive façades

4 **Multiple case study analysis**
Automated adaptive façade functions in practice - Case studies on office buildings

Priority list of extensively automated façade functions

5 **Experiment**
Prototype of a cyber-physical façade system

Prototype

Practical result

Example architecture for a Cyber-physical façade system

6 **Conclusion**

7 **Final remarks**

3 Superposition matrix for the assessment of performance-relevant adaptive façade functions*

The study in Chapter 2 provides an overview of both topic fields, intelligent façades and intelligent technical systems in industry. In addition to an understanding of the terms used, it also estimates the development stage in the respective application field. One finding is that by the fourth industrial revolution a new development stage has been reached that is not yet achieved in the field of façades as automated systems. Cyber-physical systems were identified as a key driver of this development. A general potential in the networking of façade functions based on the model of intelligent technical systems in the industry becomes evident when considering the multi-functionality of the façade. In addition to the identification of functions that contribute to performance in their active implementation, information is also required on which data must be collected from the façade with regard to influencing factors and requirements, in order to identify façade functions as part of a cyber-physical implementation of façades. It is unclear which functions can be considered in such a cyber-physical implementation. The following abstract outlines the research investigation carried out.

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* The chapter is based on a manuscript that was previously published as journal article: Boeke, J., Knaack, U., & Hemmerling, M. (2019). Superposition matrix for the assessment of performance-relevant adaptive façade functions. *Journal of Facade Design and Engineering*, 7(2), 1-20. ISSN 2213-3038. doi:10.7480/jfde.2019.2.2463.

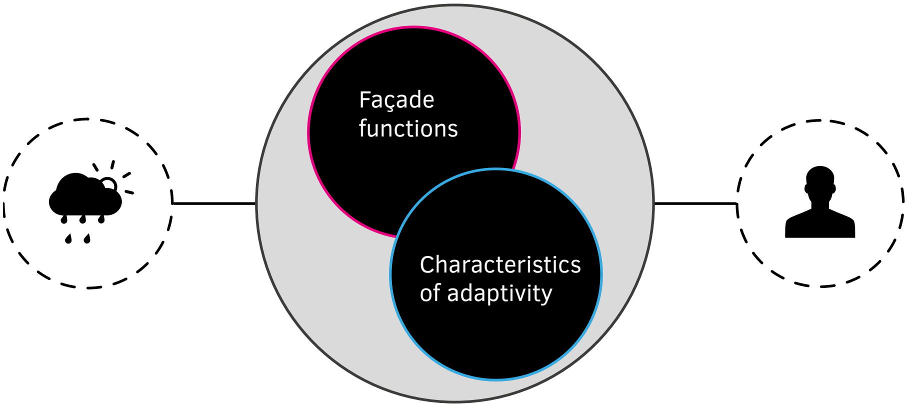

FIG. 3.1 Graphical abstract of the second research investigation

The environmental boundary conditions and the demand for comfort change constantly during the use of a building. By dynamically balancing changing conditions and requirements, adaptive façades contribute to the energy efficiency of buildings. The façade fulfils a multitude of functions that are interdependent and relate to environmental conditions and requirements. By negotiating mutually supportive and competing adaptive functions, intelligent coordination offers the potential for better performance of façades in building operation. The strategy is already being applied in other application areas, such as the intelligently cooperating machines in Industry 4.0. There, individual automated production plants are networked to form intelligent technical systems with regard to a common production goal. The research presented follows the assumption that this strategy can be applied to automated and adaptive functions of the façade to increase the building performance. The study identifies those functions which, due to possible automation and adaptivity, as well as effect on performance, can be considered as possible components of an intelligently cooperating system. In addition, characteristics are determined which can be used to evaluate the extent of automation and adaptivity of an individual façade function. The study shows that a detailed analysis of the automation and adaptivity within identified façade functions is possible. With a superimposition matrix, it also provides a tool that enables this assessment of the degree of automation and adaptability.

3.1 Background

The façade determines the overall performance of the building. It has an impact on the indoor comfort and the buildings' energy efficiency. In view of current objectives related to energy saving and the increased demands on the well-being of users within buildings, there is a demand for more efficient façade systems. Researchers see a potential in adaptive façades (Aelenei et al., 2015). The climatic conditions of the outdoor environment and the indoor requirements are constantly changing. The balancing of both presents a continuous optimisation of the construction properties with regard to the performance of the façade. This enables savings in the operation of energy-consuming building services, which can be reduced if the building envelope guarantees a desired indoor climate.

The façade fulfils a multitude of additional functions in the role of a mediator between the exterior and interior. The façade functions are derived from the influences of the environment and the requirements of building use. The façade functions are mutually interdependent. They can conflict or positively influence and complement each other. Moloney (2011) and Loonen, Trčka, Cóstola, and Hensen (2013) formulate the demand for holistic concepts instead of fragmented solutions for adaptive façades. Adaptive façades are being researched and realised, but the development is still at an early stage (Aelenei et al., 2015). The implementation of adaptive façades often includes automation technology. Over the past decades, research and development in this field provided the technical basis for the realisation of such systems (Schumacher et al., 2009). These include the miniaturisation of electronics and computer technologies, as well as the developments in sensor and actuator technologies.

The close interaction of computer-based control and communication with physical technical systems forms the concept of cyber-physical systems. An important aspect is the cooperation of distributed system components (Monostori, 2014; Rajkumar et al., 2010; Wang, Torngren, & Onori, 2015). The Internet of Things (IOT) describes the comprehensive and internet-based networking of physical objects. All devices that have an embedded control system and the ability to communicate can be part of it (Bittencourt et al., 2018). In the current development of an Industry 4.0, the flexibility and productivity of manufacturing processes is increased by networking individual production facilities into so-called intelligent technical systems. Technological developments in various research fields, such as IT and neurobiology, are merged to provide mechatronic systems with intelligence based on embedded sensors, actuators, and cognitive abilities. The individual technical systems within an intelligent technical system work autonomously and are able to communicate and cooperate with regard to a common production goal (Dumitrescu et al., 2012).

Böke, Knaack, and Hemmerling (2018) assume that such strategies can be applied to the operation of the building envelope. By networking automated adaptive façade functions within an intelligent system, the efficiency of the façade in building operation is to be increased in the sense of greater flexibility and productivity in industrial production.

For the networking, a differentiated understanding of the individual façade functions and the individual possibilities of automation and adaptivity is required. There are different lists of façade functions that do not take adaptivity into account, such as the 'façade function tree' by Klein (2013). Loonen et al. (2015), for example, provide characteristics of adaptivity for the overall system of the façade without consideration of individual functions.

3.2 Problem statement

The possibility of an intelligent cooperation of automated adaptive façade functions according to the model of networked production plants in industry has not yet been clarified. The role of an individual adaptive façade function as a component of an intelligently networked façade can only be assessed by comparing it with the project-specific environmental conditions and performance requirements.

It is uncertain which façade functions can be considered as a part of an intelligently networked system due to an adaptive feasibility and an effect on the performance of the façade. Previous listings of façade functions, like the 'façade function tree' by Klein (2013) or the 'façade as an interface' by Hausladen et al. (2005) refer to the façade generally, and differ in organisation, scope, and detail. The transfer of the networking strategy from industrial production plants to the façade depends, according to the technical basis of an Industry 4.0, on the comprehensive automation and adaptivity of the individual functions.

There is a lack of assigned characteristics by which the degree of automation and adaptivity of an individual façade function can be assessed. Previous studies on a possible characterisation of adaptive façades, such as the composition by Loonen et

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al. (2015), refer to the façade as an overall system. They do not provide a complete result, since they refer to partial aspects such as either functionality or the degree of automation.

3.3 Objectives

The aim of the study is to develop a holistic view of adaptive façades in the interplay of requirements and external boundary conditions. The knowledge about dynamically changing factors of the boundary conditions supports a later decision as to which information must be collected via sensors for the intelligent operation of a networked façade system. For this purpose, the individual factors to which the adaptive façade must react are to be recorded. In addition, the various requirements for interior comfort are to be compiled as target values for the intelligently networked façade system.

Façade functions that can be automated and adaptive, and that affect the performance of the façade, meet the requirements for a possible cooperation with other façade functions within a networked system. One aim of this study is to identify these façade functions and assign characteristics to assess the degree of an automated adaptivity.

As a tool for the subsequent examination of the actual requirements in practice, the identified façade functions are to be superimposed with the identified characteristics of automation and adaptivity in a superposition matrix.

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3.4 Research question

Main question:

- **How can the automated adaptivity of façade functions be assessed to systematically identify them as a possible part of an intelligently networked façade?**

Sub questions:

- What are the boundary conditions of an intelligently networked façade and from which environmental conditions and comfort requirements derive its adaptive functions?
- Which façade functions are possible part of an intelligently networked façade due to a possible adaptive implementation and an impact on the building performance?
- How can the automated adaptivity of a façade function be assessed?

3.5 Methodology

The investigation is based on a literature review. It is organised into two main parts. In the first part, under Section 3.6, the boundary conditions of an intelligently networked façade are recorded in response to the first sub question. These include the environmental conditions with dynamic parameters, as well as the different requirements for interior comfort. Both fields are extensively researched and documented in literature and standards. This first section, as shown in FIG. 3.2, provides the context for the subsequent assessment of whether a façade function can be implemented automated adaptive and whether it has an effect on building performance.

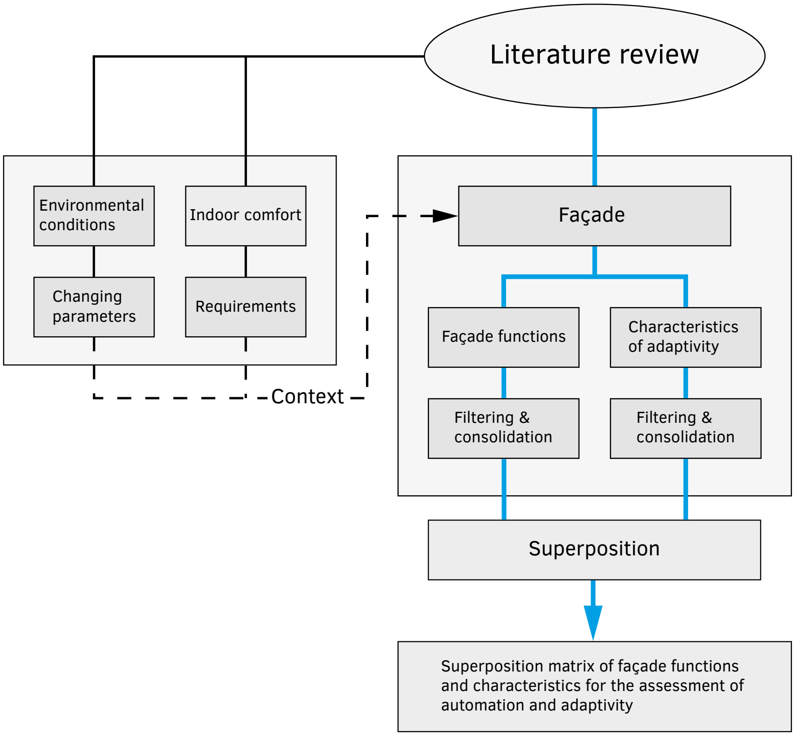

FIG. 3.2 Methodology diagram of the second study: Superposition matrix for the assessment of performance-relevant adaptive façade functions

A focus of the study is on the automated adaptive façade functions examined in the second part in Section 3.7. Previous lists such as the 'façade function tree' by Klein (2013) contain an overview of all façade functions without restriction as to whether an adaptive implementation is feasible and whether it affects the performance of the building envelope. The list 'façade as an interface' by Hausladen et al. (2005) corresponds to the approach of classifying façade functions in a holistic view, taking environmental conditions and comfort requirements into account. It serves as a starting point for the identification of relevant façade functions in this study. In order to ensure the completeness and accuracy of the functions identified by them, the list is overlaid with alternative layouts developed by Klein (2013) and in the research of mppf - The multifunctional plug&play approach in facade technology (2015). The overlaid data sets of façade functions is consolidated and filtered, as shown in Table 3.1 of Section 3.7.1, according to performance relevance as well as a basically possible adaptivity. The identification of characteristics that can be used to assess the automated adaptivity of a façade function is also based on existing literature. Different references are overlaid and consolidated based on the research by Loonen et al. (2015) with the goal of a complete list of evaluation characteristics of automation and adaptivity.

For the assessment of the automated adaptivity, the determined characteristics are assigned to the previously identified individual façade functions. This step is done regarding the third sub question in a systematically structured superposition matrix according to the representation in FIG. 3.3. The usability of the superposition matrix is tested on the basis of an exemplary application to an existing façade project. The necessary project information for the application example is derived from literature.

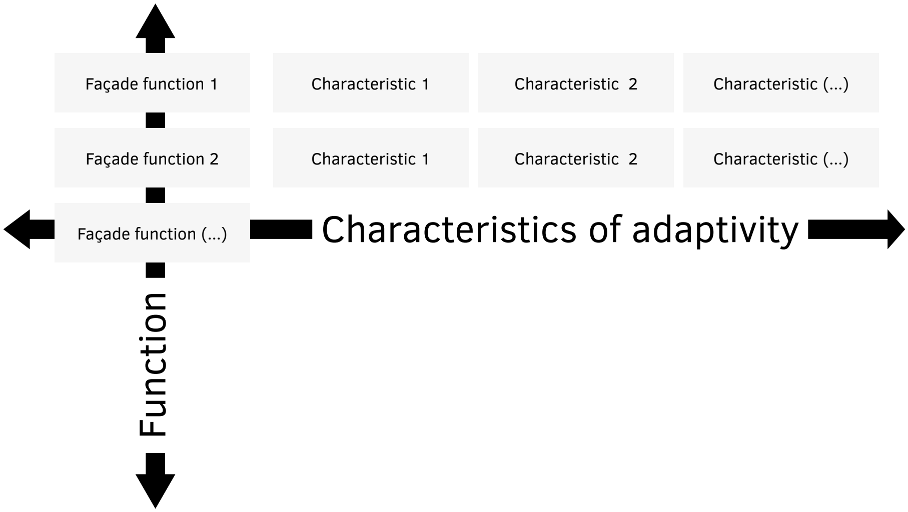

FIG. 3.3 Schematic representation of the superposition matrix

3.6 The context of environmental boundary conditions and comfort requirements

3.6.1 Identification of environmental boundary conditions and related dynamic parameters

The climate is composed by the variations of different elements. According to Dahl (2010), the detached discussion of individual aspects is difficult since they are in a constant and dynamic relationship to one another. Bitan (1988) identifies temperature, humidity, wind, precipitation, solar radiation, and special features as parameters with a high impact on the building. Hausladen, Liedl, and Saldanha (2012) designate the same climate elements as the most important for the construction planning, but without the addition of 'special features'. In the consideration of the 'façade as an interface' Hausladen et al. (2005) designate the sound as an influencing element. van den Dobbelsteen, van Timmeren, and van Dorst (2009) also supplement this aspect. Dahl (2010) focusses on, from his point of view, the most important aspects: heat, humidity, wind, and light.

In an overarching view, the following climate elements relevant to the building industry are identified. With regard to the adaptivity of the façade, the focus is on the dynamic parameters of an environmental condition.

Solar radiation

Solar radiation is electromagnetic radiation emanating from the sun (Givoni, 1976). The energetic radiation power determines the intensity of the solar radiation. It changes with respect to the time of day or season as well as to the weather. Another important aspect is the duration of irradiation, depending on the geographical location and the weather (Ranft & Frohn, 2004). Global radiation is composed of direct sunlight and indirect, diffuse radiation. The angle of incidence of the direct sunlight is another important aspect. The greatest amount of energy is released at an incidence angle of 90 degrees to a surface. The intensity, the duration of irradiation, and the angle of incidence of the irradiation can be summarised as the important parameters of the solar radiation.

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Temperature

Solar radiation indirectly affects the outside air temperature by heating the earth's surface. This provides heat energy to the air layers above. Also, the exchange with inflowing air affects the temperature. Depending on the geographic location, the season, and the time of day, the temperature is subject to great variations. Between 1.5 and 3 m depth, the average temperature of the ground remains constant throughout the year (Givoni, 1976; Hausladen et al., 2012). The air temperature measured in degrees Celsius is determined as the decisive parameter of this climatic element.

Air quality

The air quality is determined by its oxygen content as well as its pollution. Air pollution occurs mainly in dense urban areas as a result of traffic or industrial processes. Plants can also be the cause of reduced air quality due to the formation of pollen (Hasselaar, 2013).

Sound

Developments in both transport and industry are accompanied by noise emissions. Due to the density of urban areas noise pollution can often not be avoided. Noise in the environment has an impact on human comfort and depends on the distance between the source and the building. Sound differs by type, duration, and transmission. Hausladen et al. (2005). distinguish linear and selective sound sources. The duration of a noise load can be continuous, interrupted, or recurring. Sound transmission can take place via air or via building components and materials. The sound applied to the building is measured outside in decibels (Hausladen et al., 2005).

Wind

Wind is an effect of the earth's air flow and pressure system. It is based on the distribution of air pressure, the rotation of the earth, the alternation of heat and cool over land and over water, and the topography of a respective region. Winds vary according to seasons. There are global wind systems like the trade-winds, westerlies, and polar winds. Additionally, time-bound winds exist due to high temperature differences. Local winds occur between water and land or mountains and valleys (Givoni, 1976). The microclimatic conditions such as terrain and building form have a great impact. For example, nozzle effects are possible, depending on the building arrangement (Hausladen et al., 2012). The pressure acting on a building

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depends on the local wind force. Force and direction of the wind are identified as crucial parameters.

Precipitation

Precipitation is a component of the water cycle. Depending on the temperature, the water changes its form from gaseous to liquid. The cooling of the air condenses the moisture stored in it and leads to precipitation. The dew point is the temperature at which this process takes effect. Along with rain, mist and dew are also forms of precipitation (Givoni, 1976). The precipitation quantity and the possible precipitation direction are identified as parameters of the climate element.

Humidity

Humidity is defined as either relative humidity or absolute humidity. Absolute humidity refers to the location-related, stored water vapour in the air. It is dependent on precipitation and the distance to the sea. Absolute humidity is constant during the day, while relative humidity is subject to temperature fluctuations. Cold days have a decreasing effect, warm days have an increasing effect (Hausladen et al., 2012).

3.6.2 Identification of requirements for the indoor comfort

The comfort in buildings can be in conflict with energetic performance goals. The quality of an interior climate has a significant impact on the well-being, health, and productivity of users. The demands on the interior climate of a building are guided by the needs of the comfort of the human being. They vary according to subjective perceptions and preferences (Ranft & Frohn, 2004). Comfort can be determined by a range of factors, some of which are related to each other in a way that is not scientifically understandable (Ranft & Frohn, 2004).

Essential aspects of comfort are, according to Knaack et al. (2014), perceived temperature, visual comfort, hygienic comfort, and acoustic comfort. A clear assignment of the aspects relevant to a user’s comfort cannot be determined universally due to varying individual perceptions. In order to determine the climatic quality of an interior environment, specialist planners rely on the level of satisfaction of users (Hasselaar, 2013). In many cases, there are legal requirements that a building must meet. In Germany, minimum requirements for the indoor climate are defined in the following guidelines and standards: Important for the evaluation of interior comfort are ANSI/ASHRAE 55 - Thermal Environmental

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Conditions for Human Occupancy and DIN EN 15251 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics; German version EN 15251:2007. For indoor environments in general, the ISO 7730 defines requirements with regard to thermal comfort and DIN 5035 with regard to daylight. Requirements for comfort in office buildings are defined by the standards DIN1946 and DIN 33403: 'Climate at the workplace'. The acoustic requirements in office buildings are regulated by DIN 2569: Sound insulation in office buildings (Ranft & Frohn, 2004). Al horr et al. (2016) identify the thermal comfort, acoustic comfort, and visual comfort as important factors for the well-being and productivity of users. Dahl (2010) complements aero-comfort and hydro-comfort in terms of the indoor air quality.

Thermal comfort

The operative temperature, also known as the sensed temperature determines the thermal comfort and is composed of the radiation and air temperature of the room (Hasselaar, 2013). It is often understood as the most important aspect in terms of interior comfort. The human body maintains an operating temperature of about 37 degrees Celsius (Dahl, 2010). Hausladen et al. (2008) determine the operative temperature in combination with the air speed as decisive factors for the thermal comfort. Al horr et al. (2016) name air temperature, average radiation temperature, relative humidity, air speed, and individual aspects such as clothing as the six influencing factors that affect thermal comfort. An uneven distribution of the room temperature leads to discomfort. The activity of a person, clothing, age, sex, health and duration of stay in an environment influence, according to Hausladen et al. (2005), the sensitivity towards temperature. Too high temperatures can weaken the performance of a person while cold temperatures lead to illness. Hausladen et al. (2005) formulate the following temperatures as average demand values separated by winter and summer season: In winter, the comfortable operating temperature is 22C° at air speeds of approx. 0.16m/s, while in summer it is 24C° with an air speed of 0.19m/s.

Aero- and hydro-comfort

According to Dahl (2010), comfort also depends on air movement and cooling, both of which occur with convection and evaporation. As the temperature increases, larger air movements are perceived as positive (Ranft & Frohn, 2004). The quality of the indoor air is based on the quality of the ventilated external air and possible influences by users, technical installations, materials, or indoor plants. Air pollution outdoors can have a negative effect on the air supply. High-quality air is based on a high oxygen concentration and a low dust and pollution load. The perceived contamination of indoor air is measured in Decipol (Dp). The CO2 concentration is also an aspect of air quality. In addition to the activity of the user, Hausladen et al. (2008) also name behaviours such as smoking as an influencing factor. The perceived quality of the air decreases with increasing humidity and temperature. The olf measure corresponds to the air pollution of a user doing light office activities. Hausladen et al. (2008) give 0.15vol% as the maximum CO2 concentration. Dahl (2010) describes the hydro-comfort with regard to the humidity. Relative humidity can be subject to large fluctuations between about 20% and 70%. It has an impact on health and how people feel within interior climates. Large rooms can more easily compensate for humidity due to a larger air capacity, whereas small rooms require more extensive air exchange (Dahl, 2010; Ranft & Frohn, 2004).

Visual comfort

Hausladen et al. (2008) establish that natural light has a positive effect on the visual comfort of users. According to them, the quantity of the light provided, and its distribution, are crucial. The human eye adapts to the prevailing light conditions (Dahl, 2010). Glare can have a negative impact on the user. It occurs as a result of direct radiation originating from sun or artificial light sources, as well as reflections of light irradiation. Large contrasts in the lighting also lead to possible glare.
Low contrasts and low shadows reduce it and promote spatial perception. Visual references to the outside contribute to the well-being of the users (Hausladen et al., 2008).

Acoustic comfort

Acoustic comfort is based on the protection from noise and the guarantee of a sound environment which corresponds to the use of the building (Al horr et al., 2016). Acoustics is associated with well-being and the ability to concentrate within a room. Sources of noise pollution may be outside the building or may result from the activities within a room. Sound is measured in Decibel (Db). The volume of sound is a decisive factor. The weighted sound level considers people to be more sensitive to specific frequencies than to others. The addition (A) indicates the correspondingly filtered measured variable. Silence corresponds to the value 0Db(A) and noise above 140Db(A) is perceived to be painful (Hasselaar, 2013). The reverberation time describes the duration of a noise and has a great effect. The noise should not collide with communication or concentration in a building. Hausladen et al. (2005) formulate a noise load of 30-45db(A) as an acceptable maximum.

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3.6.3 Interpretation of the identified environmental conditions and comfort requirements

A total of seven categories of environmental conditions have been identified as illustrated in FIG. 3.4. Different dynamic parameters are possible within the respective category. The influencing factors are not always subject to a natural origin but can also be the result of human intervention in the environment. Examples of such artificial influencing factors are the noise environment within urban areas or traffic-related air pollution. Depending on the project's geographical and temporal context, different patterns of influencing factors are possible. On the other hand, there are a total of four identified categories for interior comfort. Different requirements can be assigned to the individual categories. Hausladen et al. (2008) distinguish detailed requirements of the interior comfort in the 'façade as an interface'. The 'room temperature', the 'inside surface temperature', and the 'supply air temperature' named by them can be assigned to the thermal comfort. Illuminance, glare protection, and visual relationships affect the visual comfort. The aero- & hydro-comfort can be detailed into air changes, air quality, and air speed, while the sound load named by Hausladen et al. (2008) can be assigned to the acoustic comfort. It is not claimed that the listed requirements are complete. They are the basic requirements that can be supplemented depending on the conditions of different building uses. FIG. 3.4 illustrates the context of the environmental conditions and comfort requirements from which the adaptive functions of the façade derive.

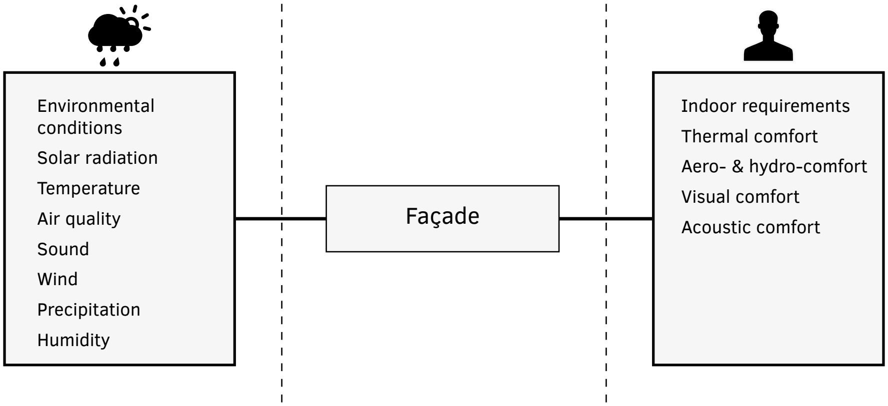

FIG. 3.4 Context of environmental conditions and comfort requirements

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The context provides a holistic view of the façade in terms of its dependence on environmental conditions and comfort requirements. It contributes to the understanding of individual reactions of an adaptive façade function. Possible intersections between the individual reactions can be identified with regard to the differentiated environmental conditions and indoor comfort requirements. The context is intended to serve as a decision aid in the selection of façade functions for networking and existing dependencies and interferences in cooperation.

3.7 Identification of façade functions and characteristics of adaptivity

3.7.1 Performance relevant and possibly adaptive functions of the façade

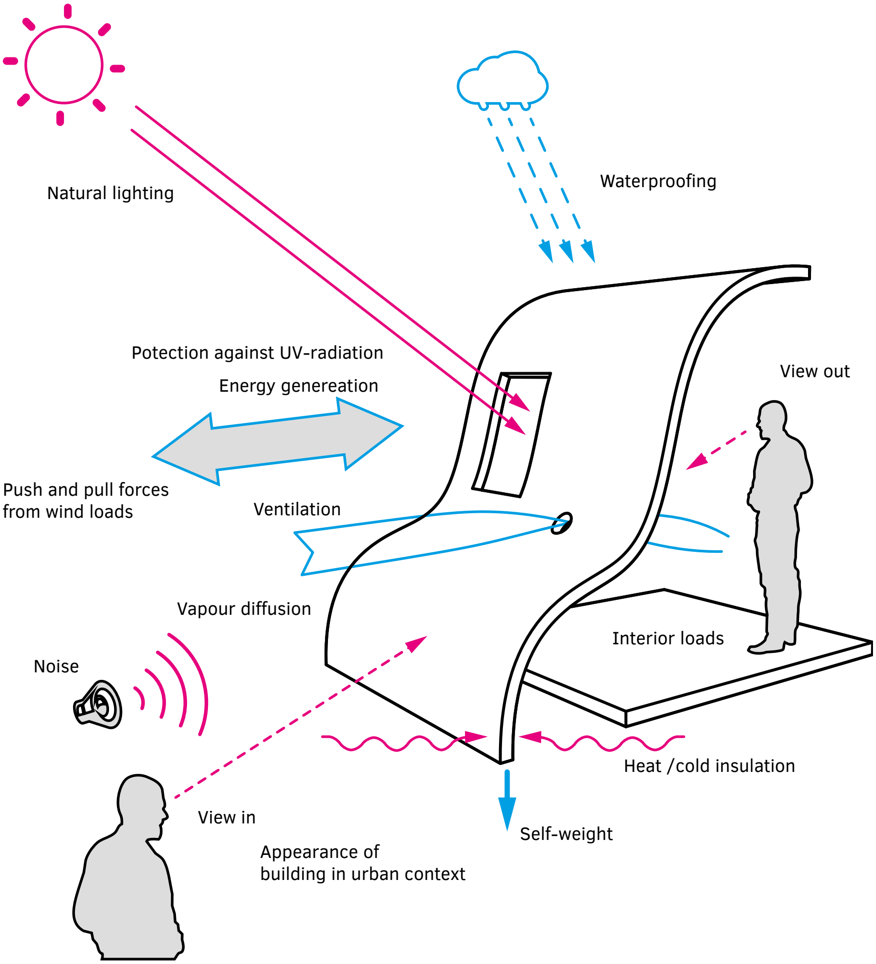

FIG. 3.5 Façade functions adopted from Knaack et al. (2014)

The façade has a great impact on the energy and comfort-related quality of a building. As shown in FIG. 3.5, it balances the dynamic climatic conditions of the exterior environment with regard to the requirements of the interior (Hausladen et al., 2008). It determines the appearance and contributes to the design assessment of a building (*Fassaden*, 2015; Knaack et al., 2014). Features of the façade can be distinguished according to whether they have an effect on the building's performance or solely on the aesthetic design of the façade. In this respect, Loonen, Trčka, et al. (2013) exclude, for example, media façades, which exclusively present visual adaptive features without contributing to the performance, from the definition of climate-adaptive building envelope.

The expectations and demands on the functional spectrum of façades continuously increased throughout the development history (*mppf - The multifunctional plug&play approach in facade technology*, 2015). At the same time, technical possibilities available for the façade construction have multiplied. Klein (2013) notes an extensive mechanisation of the façade, which, in his view, in the latest development also fulfils additional comprehensive tasks of building services. Klein (2013) describes the functions as an elementary aspect for the investigation and development of façade constructions. According to Herzog et al. (2004), the building envelope separates and filters between the outdoor environment and interior of the building. From a historical point of view, it is the job of the façade to provide protection against the dangers and the weather of the exterior. Herzog et al. (2004) state that additional requirements for the building envelope result from the local external environment and the requirements of the interior. In this context they specify further control and regulatory functions in addition to the protection function of the façade. According to Knaack et al. (2014), the façade is a dividing element between the exterior and interior, that satisfies multiple functions with the simplest structure possible. They argue that these functions include the provision of visual openings, balancing of wind loads, and load-bearing properties. Herzog et al. (2004) see the façade as an interface, which ensures a comfortable interior climate. Depending on the different requirements of different seasons, they are also confronted with a target conflict of different façade functions. Herzog et al. (2004) also identify conflicts of interest in the different requirements of different seasons. They differentiate between different requirements in summer and in winter. According to Herzog et al. (2004), it is not only crucial which functions the building envelope fulfils, but also how the functions are organised with regard to one another. The interplay of individual façade functions can allow for synergy effects. There are different, differentiated representations of the functions of a façade. They differ in scope, detailing, and organisational structure. In an overlapping composition of façade functions 'The façade as an interface', Hausladen et al. (2005) contrast the functions with corresponding influencing factors and requirements. In this way, they also manifest superimpositions, for example when façade functions are derived from several external conditions or when they affect various interior requirements. They identify a total of thirteen climate-related functions. Participating researchers of the project ‘multifunctional plug & play facade’ formulate functions of the façade in three categories. The first category refers to the basic, mainly protective and climate-related functions of the façade. Solar thermal energy and photovoltaics are listed in a separate section on energy production. In the third category, supporting functions of the façade are named. This category includes tasks such as heating, cooling, or mechanical ventilation (*mppf - The multifunctional plug&play approach in facade technology*, 2015). Klein (2013) differentiates the functions of the façade in an objective tree, based on strategies from product design. It organises the functions stepwise into primary, secondary, and support functions. The ‘Façade function tree’ represents a comprehensive and detailed breakdown of the façade functions in five categories. These include the durability of the construction, an appropriate manufacturing process, ensuring sustainability, support for building use, and the shape of the façade. It is assumed that the functions of the categories: ‘Create a durable construction’, ‘Allow reasonable building methods’ and ‘Spatial formation of façade’ can in principle not be implemented in an adaptive manner. It is also assumed that not all functions affect the performance of the building in operation. Against this background and due to the size of the composition, a pre-selection is made regarding the categories ‘provide comfortable interior climate’ and ‘responsible handling in terms of sustainability’.

The assembly of façade functions in Table 3.2 is derived from the consolidation of the previously identified lists by Hausladen et al. (2005), Herzog et al. (2004), Klein (2013) and mppf - The multifunctional plug&play approach in facade technology (2015). The layout by Hausladen et al. (2005) is already tailored to the climate related functions of the façade. It serves as the starting point for the merging with the alternative constellations. In the superposition of the compositions it becomes clear that many of the functions, which are designated identically or slightly modified, overlap. Duplicates are removed as part of the consolidation.

TABLE 3.1 Development of the consolidated and filtered list of façade functions

	Consolidated list	Filter	Action
	Sun		
1	Glazing fraction	Irrelevant to an adaptive implementation	Skipped
2	Shading	Specified to ‘Solar’	Modified
3	Solar control glass	Specification	
4	Light deflection		
5	Glare protection		
6	Control daylight radiation		
8	Allow natural lighting of interior	Allow to control	Modified
	Temperature		
9	Thermal insulation		
10	Heat insulation glass	Specification (of Thermal insulation)	Modified
11	Thermal storage mass	Irrelevant to an adaptive implementation	Skipped
12	Decentralized equipment	Is more of a property than a function	Skipped
13	Maintain air tightness	Irrelevant to an adaptive implementation	Skipped
	Air		
14	Window ventilation	Specification (Change to Ventilation)	Modified
15	Control air exchange rate	Specification	
16	Ventilate excessive heat	Specification	
	User		
17	Allow visual contact	Allow to control	Modified
	Acoustic		
18	Sound insulation	Sound insulation = reduction? Level of success	
19	Sound reduction		
20	Insulation of connection to dividing walls	Irrelevant to an adaptive implementation	Skipped
21	Insulation of floor connection	Irrelevant to an adaptive implementation	Skipped
	Energy		
22	Collect solar thermal energy		
23	Collect solar energy		
	Supply*		
24	heating	combination with cooling	Modified
25	cooling		Modified
26	humidification	combination with dehumidification	Modified
27	dehumidification		Modified
28	electricity		
29	artificial light		
30	communication		

**not dependent on outdoor climate but relevant to indoor comfort*

TABLE 3.2 Consolidated and filtered assembly of performance-related façade functions

	General function	Specification
	Sun	
1	Solar shading	
2	Light deflection	
3	Glare protection	
4	Control daylight radiation	*Provide a comfortable daylight level*
	Control natural lighting	*Allow natural lighting of interior*
	Temperature	
5	Thermal insulation	*Heat protection*
		maintain indoor temperature
	Air	
6	Ventilation	*Control air exchange rate*
		Ventilate excessive heat
	User	
7	**Control** visual contact	*Visual contact to outside*
		Visual protection for inside
	Acoustic	
8	Sound insulation	
	Energy	
9	Generate energy	*Collect solar thermal energy*
		Collect solar energy
10	Store energy	
	Supply	
11	Heating and cooling	
12	De- / humidification	
13	Electricity	
14	Artificial light	
15	Communication	

In addition, the functions are filtered as shown in Table 3.1 in consideration of the environmental factors and requirements identified in Section 3.6 according to two decisive aspects: first, an adaptive implementation must be possible in principle. This precondition is not given for example in the case of ‘glazing fraction’ listed by Hausladen et al. (2005). The function is definitively determined within the planning and manufacturing process and not dynamically changeable in the operating phase of the building. It is therefore not taken into account for the present assembly. On the other hand, the function must have an impact on the performance of the building. Within the scope of the consolidation, further decisions are made that have an impact on the result. In some cases, Klein (2013) provides the detailing of individual, opposite states of a front function. With regard to an adaptive implementation, these functions can be summarised. An example of such a merge are the functions ‘block radiation’ and ‘let radiation pass’. Correspondingly, the reduction and the insulation of sound can be combined as different degrees of fulfilment of the function. Klein formulates several of the identified façade functions with the addition ‘Allow’. With respect to an adaptive implementation of the respective function, an opposite state is assumed to be possible and the term is converted to ‘Control’. In the category ‘Responsible handling in terms of sustainability’, Klein (2013) identifies functions which do not directly affect the performance of the building. The collection of solar and solar-thermal energy can contribute to the functioning of the façade depending on the climatic conditions of the exterior. The corresponding functions are also named in the list by mppf – The multifunctional plug&play approach in facade technology (2015) and are taken into account in the consolidated summary. In the ‘Supply’ category, they also name functions of building technology, which have an effect on the interior climate, regardless of external boundary conditions. They are also added to the list of functions.

3.7.2 Characteristics of adaptivity

Loonen et al. (2015) require uniform aspects which can be used to determine the adaptiveness of a building envelope. They identify eight characteristics of adaptivity which they also assemble in a matrix. The starting point of the investigation by Loonen et al. (2015) is the adaptivity. In the first aspect, they question the goal and purpose which should be achieved with it. Loonen et al. (2015) name a total of six objectives, which are derived from the requirements of interior comfort, user control and energy generation. For each objective, they identify appropriate, responsive functions. In contrast to the listing by Loonen et al. (2015), this study is organised according to the façade functions themselves. According to the identified façade functions in context of environmental conditions and indoor comfort requirements in

Chapter 3.6 of this research, the objectives of a façade function are not questioned again. A relevant characteristic is whether a façade function can be adaptive at all. A distinction is made between the flexibility of the building envelope, i.e. the adaptivity which has to be initiated by the user, and the adaptiveness which requires independent, self-regulated adjustments (Ross, Rhodes, & Hastings, 2008). In addition, the technology, which can be a construction component or a material that carries out the function, is questioned as an aspect by Loonen et al. (2015). The accordingly named 'spatial scale' is understood to be directly coupled to it. Under 'Degree of adaptivity' they summarise the possible states of an adaptive process. These can, according to them, map the direct change between extreme states (on-off) or smooth transitions (gradients). With regard to the application to a façade function or a component, this characterisation appears to be insufficient. The question arises as to whether an open window is ON or OFF. As a supplement to this characteristic, a generalisation of the state description is proposed in 'active' and 'inactive'. Additionally, one should define when a corresponding state is reached for each function. The response time is adopted as a criterion of adaptivity. It is assumed that it provides information on whether the adaptation processes meet the dynamic requirements of a façade function. Loonen et al. (2015) identify visibility as a characteristic of an adaptive façade. As this aspect has no effect on the performance of the façade it is not taken into account in the present study. Loonen et al. (2015) distinguish between intrinsic adaptations, the construction or material inherent adaptations in response to ambient stimuli, and extrinsic adaptations, which are based on additional automation technology. From a technical point of view, therefore, the scope of introduced automation technology can also be a criterion for the capabilities of an adaptive façade function. In this context, Moloney (2011) and Ochoa and Capeluto (2008) refer to the components of a mechatronic system, an existing input system, a processing system, and an output system. An existing sensor system, which continuously collects data on the relevant environmental conditions, can be identified as a criterion for adaptive façades. Additionally, an existing control, which processes the determined data, as well as actuators, which initiate adjustments within the façade construction, are further criteria. Table 3.3 is a revised list of characteristics for the adaptivity of façades.

TABLE 3.3 Revised list of characteristics of adaptivity

	General Characteristics	Description	Possible parameters
	General		
1	Technology	The construction-related element, which ensures the fulfilment of the function.	Building component / System / Material
2	Flexible	Possible Flexibility of the construction regarding the function	Yes / No
3	Adaptive	Self-initiated adaptations (applied Automation technologies)	Yes / No
	Behaviour		
4	Operation	Component or material-integrated self-adaptation or on the basis of information processing	Intrinsic / Extrinsic
5	Response time	Time intervals of adaptation processes	Seconds, Minutes, Hours, Day-night, Seasons, Years, Decades
6	Degree of adaptivity	The number and type of possible states that the adaptive system can map.	Active / Inactive / Gradual
	Automation		
7	Input system	Existing information gathering (sensors)	Yes / No
8	Processing system	Existing processing of the gathered information (controller)	Yes / No
9	Output system	Existing actuators, which implement adaptations of the design with regard to the function	Yes / No

Using the overlapping of façade functions and characteristics of an adaptive system, a database is created in which the identified functions are organised vertically, the corresponding characteristics of adaptivity horizontally. The additionally identified specifications support the understanding of general functions and can be used for a detailing in subsequent investigations. In the present database, only the general functions are taken into account. The present breakdown of functions is made based on the assumption that they are confronted with individual dynamic factors and requirements within the façade as a holistic system.

3.8 Superposition of façade functions and characteristics of adaptivity

In the superposition matrix shown in Table 3.4, the identified façade functions are overlaid with the determined characteristics of adaptivity. The façade functions are listed vertically in the table. The respective characteristics of adaptivity contrast them in horizontal organisation.

TABLE 3.4 Superposition matrix

		General			Behaviour			Automation		
		Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptivity	Input system	Processing system	Output system
	Sun									
1	Solar shading									
2	Light deflection									
3	Glare protection									
4	Control daylight radiation									
	Temperature									
6	Thermal insulation									
	Air									
7	Ventilation									
	User									
8	Control visual contact									
	Acoustic									
9	Sound insulation									
	Energy									
10	Generate energy									
11	Store energy									
	Supply									
12	Heating and cooling									
13	De- / humidification									
14	Electricity									
15	Artificial light									
16	Communication									

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3.9 Example for the application of the superposition matrix

Table 3.5 shows the application of the superposition matrix to the façade of the KFW Westarkade in Frankfurt, Germany. The project, designed by Sauerbruch Hutton and completed in 2010, was selected because the building and the façade are extensively documented in the literature (Fortmeyer & Linn, 2014). The double façade of the building is characterised by vertical coloured blinds. It has automated ventilation flaps. A glare shield is installed in the space between the façade. Based on the literature sources, the façade functions can be assigned the characteristics of adaptivity and automation shown in Table 3.5. Characteristics which cannot be determined due to missing data are marked with N.A (González, Holl, Fuhrhop, & Dale, 2010; Winterstetter & Sobek, 2013).

The case study shows that the characteristics determined can principally be applied to buildings. An absolute assignment of a function to a particular component of the façade is not always possible, since there are undefinable overlaps between them. In the investigated project, for example, the intermediate space of the double façade influences the level of sound insulation. In this context, the opening of the ventilation flaps has an effect on the noise protection. Absorbent surfaces also contribute to the fulfilment of acoustic requirements, which, however, are not able to adapt. Such complex contexts can only be mapped abstractly, and interpretations are necessary in the assignment. This also applies to the determination of individual characteristics. Thus, the opening state of a ventilation flap can be evaluated as an active or inactive state; however, in the case of a plurality of ventilation flaps that are capable of opening, it is also possible to estimate that a gradual adaptation is present. It is necessary to clarify whether the respective evaluation refers to a single element or to the overall system.

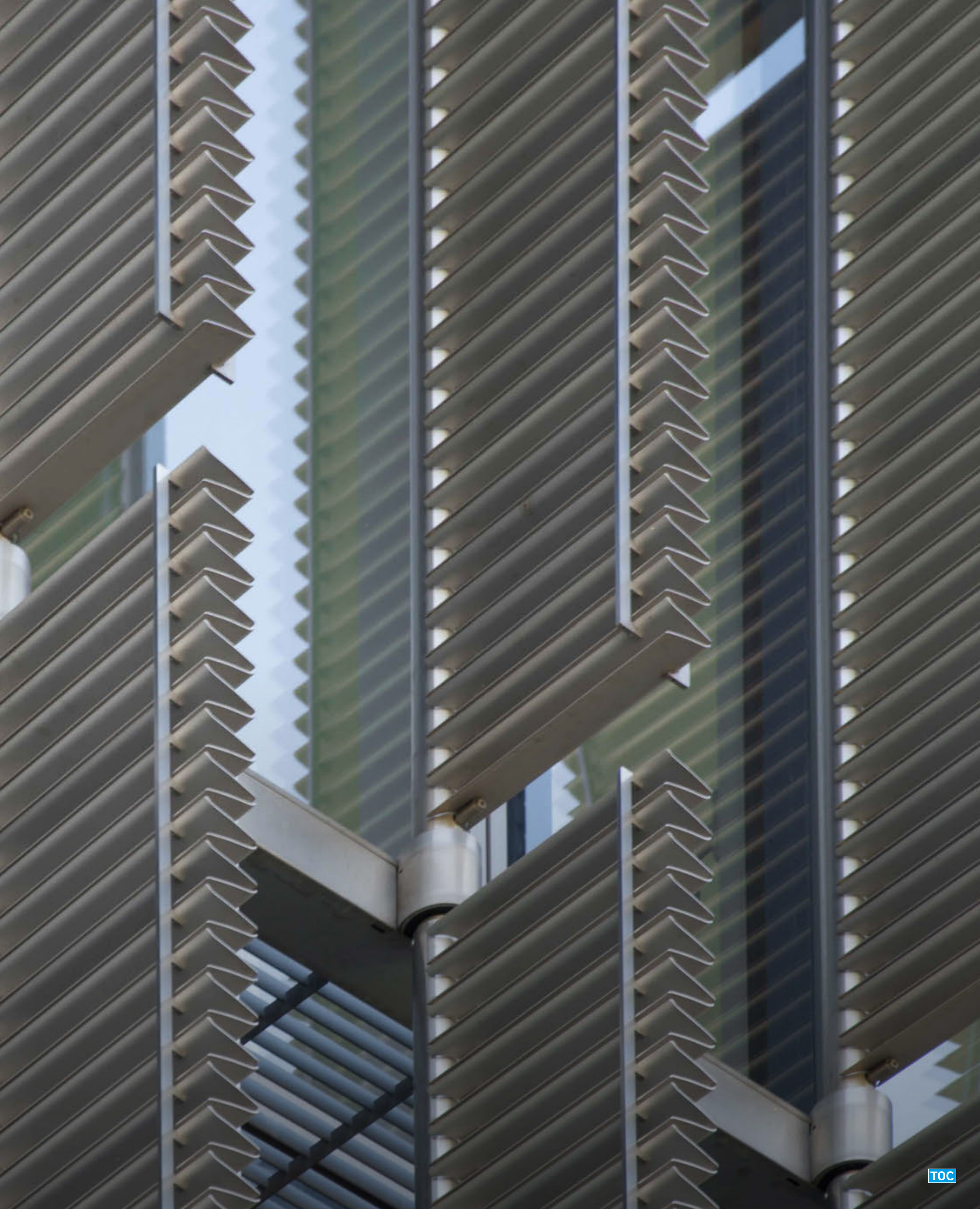
TABLE 3.5 Superposition matrix applied to the façade of the KFW Westerkade

		General			Behaviour			Automation		
		Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptivity	Input system	Processing system	Output system
	Sun									
1	Solar shading	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
2	Light deflection	No	No	No	No	No	No	No	No	No
3	Glare protection	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
4	Control daylight radiation	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
	Temperature									
6	Thermal insulation	Intermediate space	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
	Air									
7	Ventilation	Ventilation flaps	Yes	Yes	Extrinsic	N.A	Active-Inactive	Yes	Yes	Yes
	User									
8	Control visual contact	Lamella screen	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
	Acoustic									
9	Sound insulation	Absorber	No	No	No	No	No	No	No	No
	Energy									
10	Generate energy	No	No	No	No	No	No	No	No	No
11	Store energy	No	No	No	No	No	No	No	No	No
	Supply									
12	Heating and cooling	No	No	No	No	No	No	No	No	No
13	De- / humidification	No	No	No	No	No	No	No	No	No
14	Electricity	No	No	No	No	No	No	No	No	No
15	Artificial light	No	No	No	No	No	No	No	No	No
16	Communication	No	No	No	No	No	No	No	No	No

3.10 Conclusion

The study compiles the external boundary conditions and interior comfort requirements of adaptive façades. Based on existing literature, the following seven external influencing factors were identified: ‘solar radiation, temperature, air quality, sound, wind, precipitation, and humidity’. As stated above in Section 8.6.3, apart from natural factors, human intervention in the environment also has an impact on the functions of the façade. In terms of interior comfort, the four requirement categories ‘thermal comfort, aero- & hydro-comfort, visual comfort, and acoustic comfort’ were identified. The listing provides an initial basis and is not understood to be complete. Depending on the field of application and in further research, more aspects may be added. Taking the identified framework conditions into account, the study provides a detailed breakdown of performance-relevant and possibly automated adaptive façade functions as potential parts of an intelligently networked, adaptive façade system. While some of the identified functions have a direct impact on the façade performance by balancing of environmental conditions and comfort requirements, others are cited because of an existing reference to environmental conditions and an indirect impact on the system, for example, through the provision of energy. The ‘Supply’ functions category lists such functions that are not necessarily linked to external influences but do affect the interior comfort. As an extension of previously existing research results, the found characteristics of an adaptive façade as an overall system are summarised, supplemented with automation aspects, and applied to the individual functions. This detailing enables a differentiated consideration of dependencies and shared requirements between individual performance-relevant and automated adaptive façade functions within an intelligently networked façade system. The superposition matrix developed in this study can contribute to the design of intelligent-networked and multifunctional-adaptive building envelopes. As a theoretical assembly based on existing literature, it does not provide information about the actual realised automated adaptive functions in building practice. The superposition matrix can be used as organisational tool for the systematic assessment of automated and adaptive façade functions in realised building envelopes to examine the technical basis for intelligent networking. A corresponding practical investigation is identified as a future research task for the clarification of a possible intelligent cooperation of automated adaptive façade functions according to networked production plants in industry.

Metal louvres of the Q1 façade, ThyssenKrupp Quarter by JSWD architects in Essen, Germany



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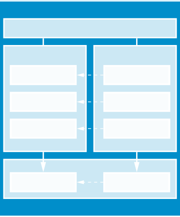
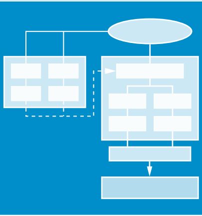
1 **Introduction**

2 **Literature review**
State-of-the-art of intelligent building envelopes in the context of intelligent technical systems



Research focus and knowledge gap

3 **Literature review**
Superposition matrix for the assessment of performance-relevant adaptive façade functions

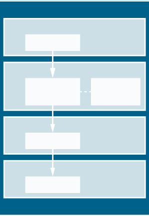


Superposition matrix

Practical result

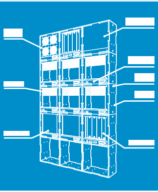
Assessment tool for automated adaptive façades

4 **Multiple case study analysis**
Automated adaptive façade functions in practice - Case studies on office buildings



Priority list of extensively automated façade functions

5 **Experiment**
Prototype of a cyber-physical façade system



Prototype

Practical result

Example architecture for a Cyber-physical façade system

6 **Conclusion**

7 **Final remarks**

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

The previous investigation identifies façade functions that are potential constituents of a cyber-physically implemented façade due to their possible automation and the execution of adaptations that affect building performance. It also provides criteria for a detailed assessment of these automations and adaptive capabilities. While the preceding study delivers theoretical knowledge on the consideration of façade functions, it remains unclear to what extent the identified functions are actually implemented in an automated and adaptive manner in building practice. In Industry 4.0, the preconditions for the implementation of cyber-physical systems lie in an already existing infrastructure of automation at the development stage of mechatronic systems. It is therefore expected that façade functions, which are already considered in the automation of façades, are particularly promising for the further investigation. It is not only interesting to know which functions are implemented at all, but also from the perspective of cooperation within the system, which functions are often jointly automated and performed adaptively. Therefore, the intended investigation of building practice does not focus on the maximum

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* The chapter is based on a manuscript that was previously published as journal article: Böke, J., Knaack, U., & Hemmerling, M. (2020). Automated adaptive façade functions in practice - Case studies on office buildings. *Automation in Construction*, 113, 103113. doi:10.1016/j.autcon.2020.103113

technically possible, but rather provides a cross-section in the general landscape of realised façade projects. Since information available in the literature is project-dependent and technical knowledge does in most cases not exist at the detailed level of individual functions, the chosen research method is interviewing experts who were involved in the project. The following paragraph provides an abstract of the study carried out.

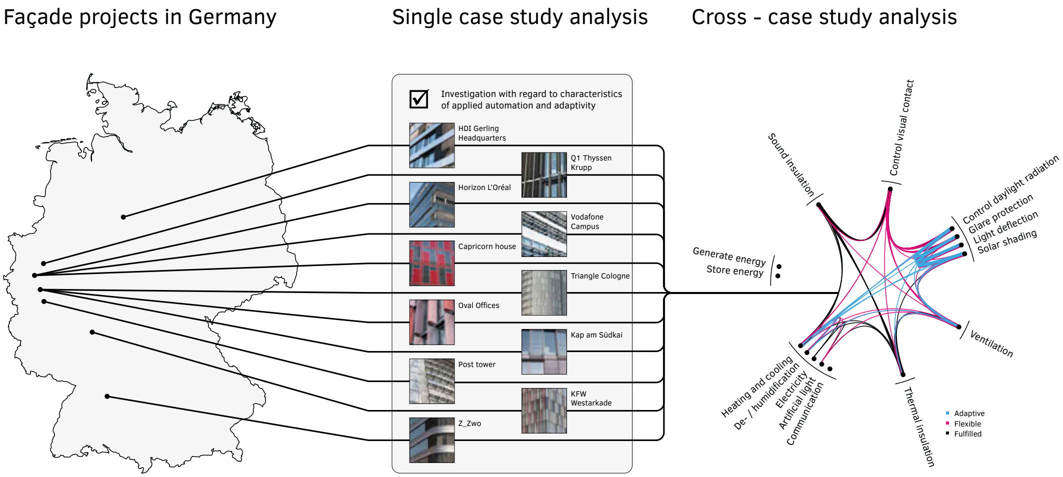

FIG. 4.1 Graphical abstract of the third research investigation

The study examines the existing technical basis in building practice for the application of cyber-physical systems to 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. Based on the type and scope of automation 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 that examines office façades in Germany. 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.

4.1 Introduction

4.1.1 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 (Domingues et al., 2016). Building automation is organized hierarchically. Kastner et al. (2005) 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 (Aelenei et al., 2015). The façade function tree developed by Klein (2013) 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, Lelieveld, and Teuffel (2011), 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 (Czichos, 2015; Moloney, 2011). 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.

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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 (Dumitrescu et al., 2012). 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, decentralized energy supply or robot-based surgery (Monostori, 2014; Wang et al., 2015). One field of application are intelligent technical systems in the manufacturing industry. The application of artificial intelligence to mechatronic production plants and the networking of individual machines towards 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 (*BITKOM, VDMA, ZVEI: Umsetzungsstrategie Industrie 4.0*, 2015).

The current development of intelligent technical systems in the manufacturing industry is based on the existing infrastructure of a former mechatronic industrial production (*Design Methodology for Intelligent Technical Systems*, 2014). 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. (2016) 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. (2018) 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, Knaack, and Hemmerling (2019) 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.

4.1.2 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.

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

4.2 Methodology

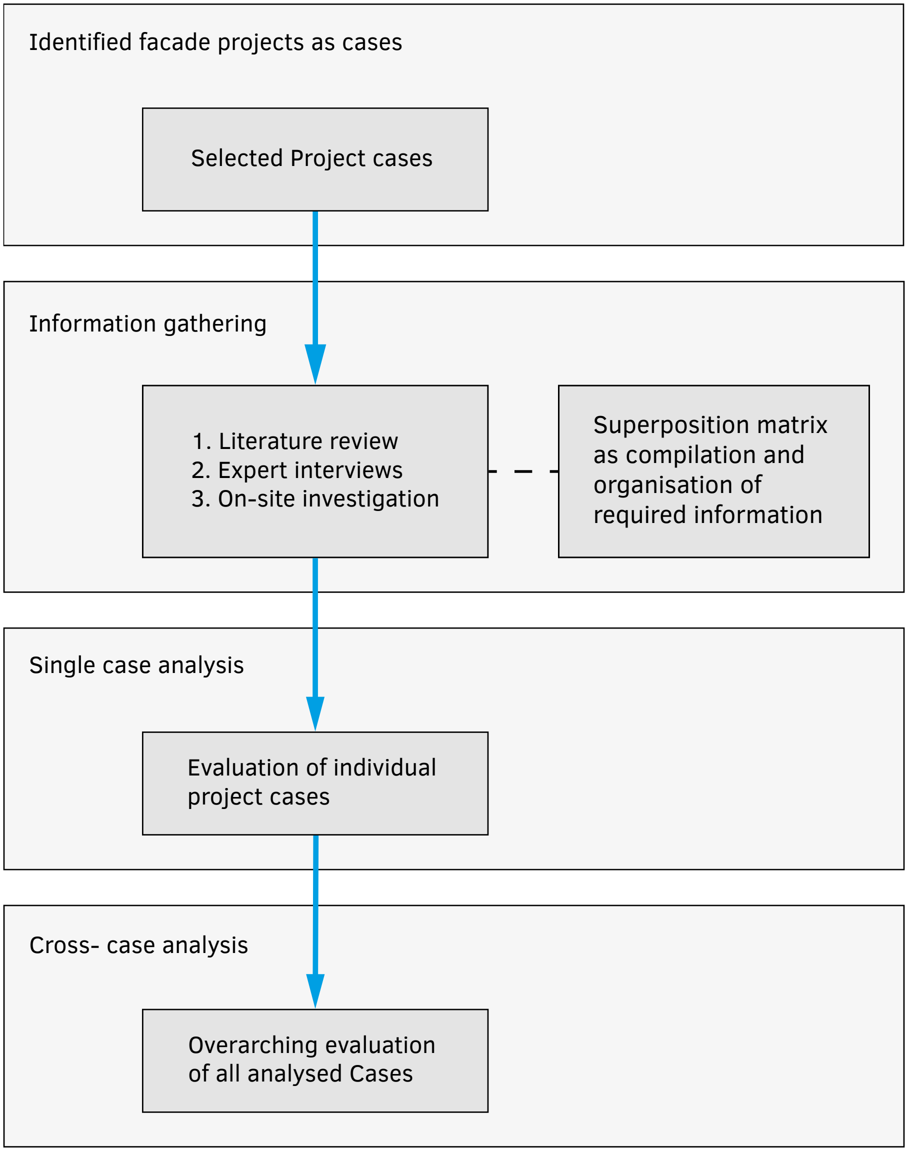

FIG. 4.2 Methodology diagram of the third study: Automated adaptive façade functions in practice – A multiple case study analysis on office buildings in Germany

The study presents a multiple case study analysis. Inspired by the case study of intelligent façades conducted by Wigginton and Harris (2002), it examines a total of eleven realised façade projects with regard to automated adaptivity. As shown in the methodology diagram in FIG. 4.2, a superposition matrix developed by Böke et al. (2019) 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.

4.2.1 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 have 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.

4.2.2 Collection of data

The study follows the principles of data collection formulated by Yin (2017) 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. (2019).

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4.2.2.1 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.

4.2.2.2 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 organized 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 organized. 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. 4.3 from the Superposition Matrix developed by Böke et al. (2019).

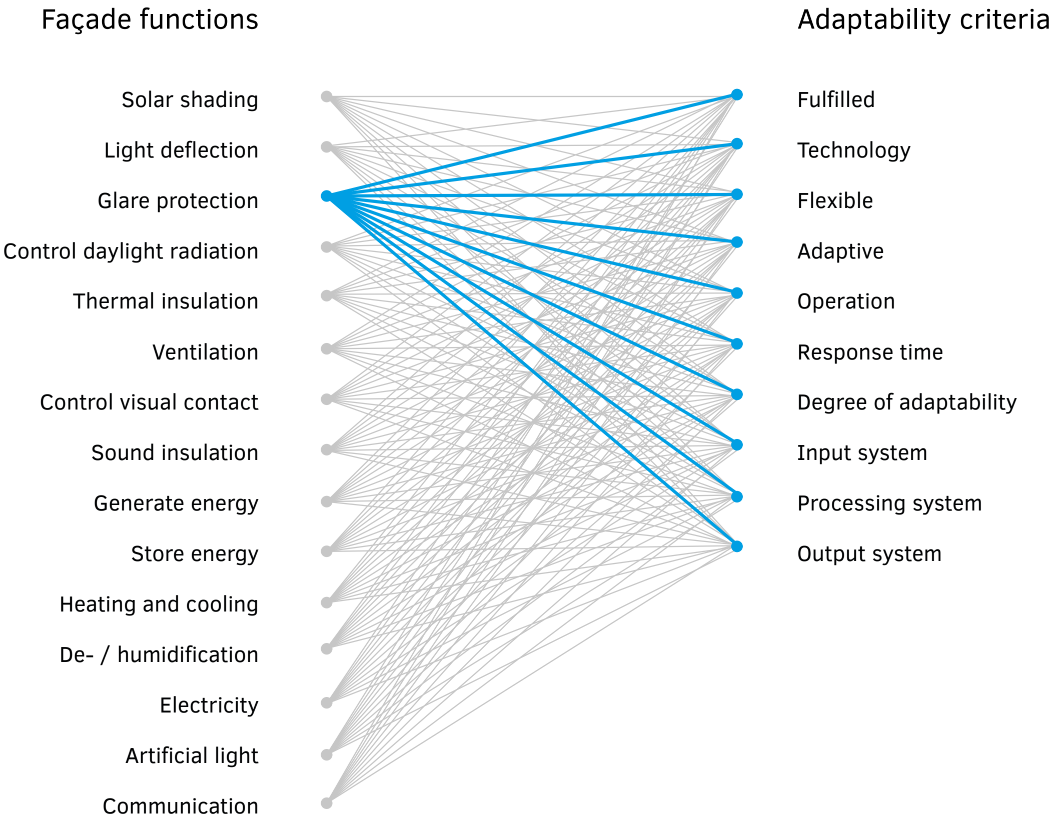

FIG. 4.3 Systematic assignment of façade functions with criteria of their adaptivity

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. (2019), 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 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. (2015) 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. The following Table 4.1 shows the actual formulation of the function related questions and the assignment of corresponding answers.

TABLE 4.1 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

According to Bogner, Littig, and Menz (2014), 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.

4.2.2.3 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.

4.2.2.4 Protocol

Table 4.2 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.

TABLE 4.2 Protocol of research investigations

#	Project	Interview partner	Affiliation	Background	Date of interview	Field investigation
1	Triangle Cologne	Möllering, C.	Enervision GmbH	System integrator	23 July 2018	06 February 2018
2	Q1 Thyssen Krupp Headquarter	Möllering, C.	Enervision GmbH	System integrator	23 July 2018	02 July 2018
3	Oval Offices	Möllering, C.	Enervision GmbH	System integrator	23 July 2018	05 February 2019
4	Z_Zwo	Becker, E.	Eike Becker_ Architekten	Architect	31 June 2018	08 February 2019
5	KFW Westarkade	Auer, T.	Transsolar	Energy consultant	02 October 2018	06 February 2018
6	Post tower	Cook, S.	Jahn	Architect	22 October 2018	03 February 2019
7	Kap am Südkai	Zimmermann, M.	Michael Zimmermann & Co. GmbH	Architect	26 November 2018	16 February 2018
8	HDI Gerling Headquarters	Bruder, B.	Ingenhoven architects	Architect	11 December 2018	15 February 2019
9	Horizon L'Oréal Headquarters	Heimann, S.	HPP Architekten GmbH	Architect	31 August 2018	23 February 2019
10	Vodafone Campus	Heimann, S.	HPP Architekten GmbH	Architect	31 August 2018	23 February 2019
11	Capricorn house	Gaessler, S.	GATERMANN + SCHOSSIG Architekten GmbH	Architect	28 January 2018	02 July 2018

4.2.3 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 (Yin, 2017). 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 FIG. 4.4.

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	— Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.4 Legend for the single project chart

The single case evaluation is followed by a cross-case analysis of all investigated projects. According to Stake (2005), 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.

4.2.4 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.

4.3 Results

4.3.1 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. FIG. 4.5 provides an overview of the following investigated porjects:

- Triangle Cologne
- Q1 Thyssen Krupp Headquarter
- Oval Offices
- Z_Zwo
- KFW Westarkade
- Post Tower
- Kap am Südkai
- HDI Gerling Headquarters
- Horizon L'Oréal Headquarters
- Vodafone Campus
- Capricorn House

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1 Triangle Cologne

2 Q1 Thyssen Krupp Headquarter

3 Oval Offices

4 Z_Zwo

5 KFW Westarkade

6 Post Tower

7 Kap am Südkai

8 HDI Gerling HQ

9 Horizon L'Oréal HQ

10 Vodafone Campus

11 Capricorn house

FIG. 4.5 Overview of the examined projects

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4.3.1.1 Case Triangle Cologne

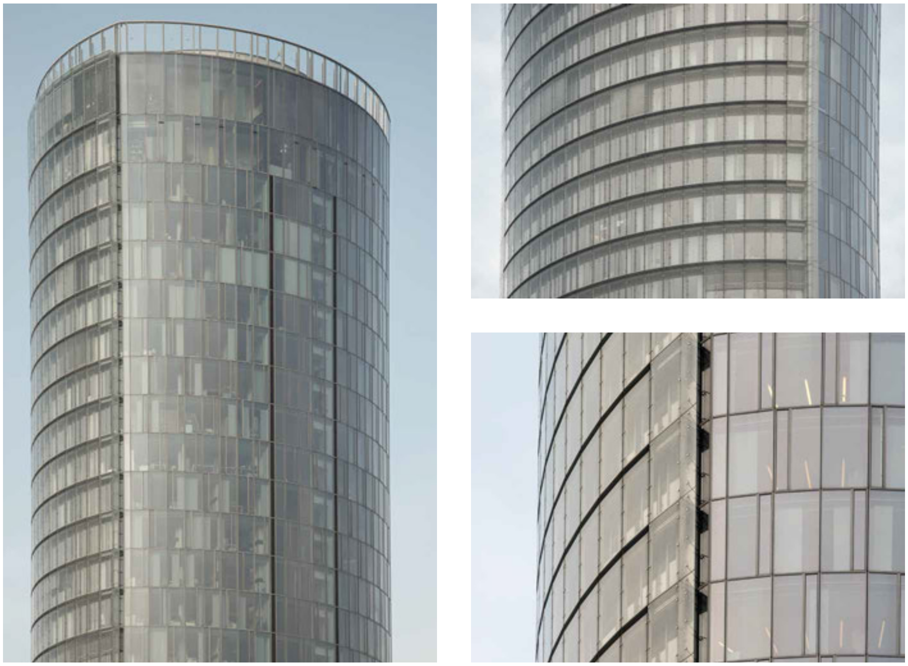

FIG. 4.6 Triangle Cologne by Gatermann + Schossig

Architects Gatermann + Schossig designed the high-rise building, completed 2007 in Cologne. The building consists of the tower building and a pedestal building. It comprises office spaces and a conference centre. The top floor is available to the public as a viewing platform (Weiss, 2010). FIG. 4.6 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 decentralized operation of the components, which are centrally parameterized. A visual feature are 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. 4.7 shows the detailed evaluation of the project based on the expert interview (C. Moellering, personal communication, July 23, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**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	●	●	●
2	**Thermal insulation**	●	Double facade	○							
3	**Ventilation**	●	Double facade & Windows	●	○						
4	**Control visual contact**	●	Lamella in double facade	●	○	E	MIN	G	●	●	●
5	**Sound insulation**	●	Double facade	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	**—** Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.7 Evaluation of the Triangle Cologne

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4.3.1.2 Case Q1 Thyssen Krupp Headquarter

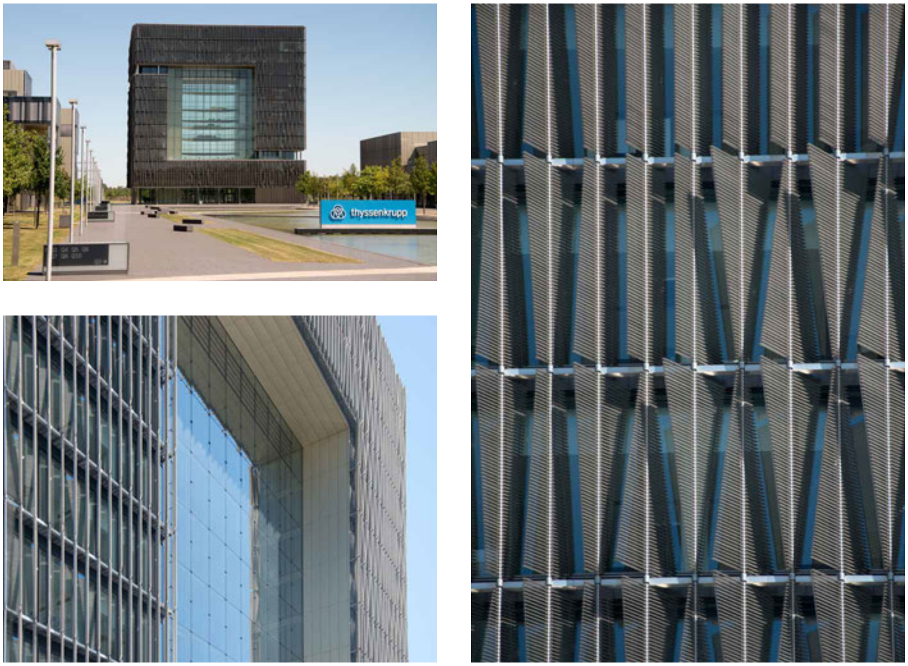

FIG. 4.8 Q1 Thyssen Krupp Headquarter by JSWD architects

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. 4.8 shows, they determine the appearance of the building. With their possible rotation, regulated by 1280 engines they are identified in FIG. 4.9 as the only adaptive components of the project [23]. 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 decentralized control are configured centrally (C. Moellering, personal communication, July 23, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	Vertical lamella	●	●	E	MIN	G	●	●	●
	Light deflection	○									
	Glare protection	●	Vertical lamella	●	●	E	MIN	G	●	●	●
	Control daylight radiation	○									
2	**Thermal insulation**	●	Facade	○							
3	**Ventilation**	○									
4	**Control visual contact**	●	Vertical lamella	●	○	E	MIN	G	●	●	●
5	**Sound insulation**	●	Facade	○							
6	**Generate energy**	–									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	– Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.9 Evaluation of Q1 Thyssen Krupp Headquarter

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4.3.1.3 Case Oval Offices

FIG. 4.10 Oval Offices by Sauerbruch Hutton

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 (Dawson, 2011). The shutters shown in FIG. 4.10 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 decentralized control concept takes place centrally. The automated façade functions are not coordinated with each other. The control system is organized in sections, and not embedded in the shutters. Following Moellering, it still presents a highly decentralized system. The opening and closing of the shutters can be manually overridden for each room. The building envelope fulfils the functions of

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sound and thermal insulation in a static implementation. As FIG. 4.11 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 (C. Moellering, personal communication, July 23, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	Shutters	●	●	E	MIN	G	●	●	●
	Light deflection	○									
	Glare protection	●	Shutters	●	●	E	MIN	G	●	●	●
	Control daylight radiation	○									
2	**Thermal insulation**	●	Facade	○							
3	**Ventilation**	●	Windows	●	○						
4	**Control visual contact**	●	Shutters	●	○	E	MIN	G	●	●	●
5	**Sound insulation**	●	Facade / Shutters	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	**—** Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.11 Evaluation of Oval Offices Cologne

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4.3.1.4 Case Z_Zwo

FIG. 4.12 Z_Zwo in Stuttgart by Eike Becker architects

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. 4.12, the building is characterized 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 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. 4.13 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 (E. Becker, personal communication, June 31, 2018) (Becker, Biesenbach, Humpert, & Schuler, 2012).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	External jalousie	●	●	E	–	G	●	●	●
	Light deflection	●	External jalousie	●	●	E	–	G	●	●	●
	Glare protection	●	External jalousie	●	●	E	–	G	●	●	●
	Control daylight radiation	●	External jalousie	●	●	E	–	G	●	●	●
2	**Thermal insulation**	●	Glass facade	○							
3	**Ventilation**	●	Windows + ventilators	●	●	E	DM	G	●	●	●
4	**Control visual contact**	●	Windows & External jalousie	●	○	E	–	G	●	●	●
5	**Sound insulation**	●	Facade & Windows	●	○	E	–	G	●	●	●
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	E Extrinsic	G Gradual	SEC Seconds	H Hours	M Months	– Not available
○ No	I Intrinsic	X On-Off	MIN Minutes	D Days	Y Years	

FIG. 4.13 Evaluation of the Project Z-ZWO in Stuttgart

4.3.1.5 Case KFW Westarkade

FIG. 4.14 KFW Westarkade by Sauerbruch Hutton

Sauerbruch Hutton designed the main building of the KFW bank and completed it in 2010. It is a 60m high-rise building on a pedestal building (Fortmeyer & Linn, 2014). 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. 4.14 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

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direction. The stepped geometric structure and the double-cladding of the façade affect the interior 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 (González et al., 2010; Winterstetter & Sobek, 2013). FIG. 4.15 shows the detailed evaluation of the project on the basis of the interview with T. Auer (Personal communication, October 02, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**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	●	●	●
2	**Thermal insulation**	●	double facade	●	●	E	H	G	●	●	●
3	**Ventilation**	●	Ventilation flaps and windows	●	●	E	H	G	●	●	●
4	**Control visual contact**	●	sun shading lamellas	●	○	E	H	G	●	●	●
5	**Sound insulation**	●	Absorber in double facade	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	2 Temperature	3 Air	4 User	5 Acoustic	6 Energy	7 Supply
● Yes	E Extrinsic	G Gradual	SEC Seconds	H Hours	M Months	– Not available
○ No	I Intrinsic	X On-Off	MIN Minutes	D Days	Y Years	

FIG. 4.15 Evaluation of the KFW Westarkade

4.3.1.6 Case Post Tower

FIG. 4.16 Post tower in Bonn by Murphy & Jahn architects

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 (2004), 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. 4.17, the façade also fulfils supply functions such as heating, cooling, humidification and dehumidification. Convectors are integrated into the floors of the building, 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. 4.16 shows that, contrary to the north side, the façade

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elements on the south side are arranged imbricated for better air circulation (Blaser, 2004). The coordination of the façade-integrated ventilation flaps is also centrally controlled (S. Cook, personal communication, October 22, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	Lamellas in double facade	●	●	E	SEC	G	●	●	●
	Light deflection	○									
	Glare protection	●	Lamellas in double facade	●	●	E	SEC	G	●	●	●
	Control daylight radiation	○									
2	**Thermal insulation**	●	Double facade / Inner glass layer	○							
3	**Ventilation**	●	Windows + Convectors	●	●	E	—	G	●	●	●
4	**Control visual contact**	●	Lamellas in double facade	●	○	E	—	G	●	●	●
5	**Sound insulation**	●	Double facade	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	●		●	●	E	—	—	●	●	●
	De- / humidification	●		●	●	E	—	—	●	●	●
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	— Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.17 Evaluation of the Post tower in Bonn

4.3.1.7 Case Kap am Südkai

FIG. 4.18 Kap am Südkai KSP Engel und Zimmermann

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 (*Complex*, 2004; *Projects 2010 / KSP Jürgen Engel Architekten*, 2010). 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. 4.18. Automation technology is used in the building 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. 4.19 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

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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 (M. Zimmermann, personal communication, November 26, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	sun shading lamellas	●	●	E	SEC	G	●	●	●
	Light deflection	●	sun shading lamellas	●	●	E	SEC	G	●	●	●
	Glare protection	○									
	Control daylight radiation	●	sun shading lamellas	●	●	E	SEC	G	●	●	●
2	**Thermal insulation**	●	Double facade	○							
3	**Ventilation**	●	Window	●	○						
4	**Control visual contact**	●	sun shading lamellas	●	○	E	SEC	G	●	●	●
5	**Sound insulation**	●	Front impact pane	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	**—** Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.19 Evaluation of the building Kap am Südkai

4.3.1.8 Case HDI Gerling Headquarters

FIG. 4.20 HDI Gerling Headquarters by Ingenhoven Architekten

The headquarters of the HDI-Gerling Insurance Group is located in Hanover. The building, designed by Ingenhoven Architekten, was completed in 2011 (FIG. 4.20). 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 (Brensing, 2012). FIG. 4.21 shows the evaluation of the interview conducted with Bruder (B. Bruder, personal communication, December 11, 2018).

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		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	External sun blinds	●	●	E	SEC	G	●	●	●
	Light deflection	●	Light deflection lamellas	●	●	E	SEC	G	○	●	●
	Glare protection	–									
	Control daylight radiation	●	External sun blinds	●	●	E	SEC	G	●	●	●
2	**Thermal insulation**	●	Triple glazing	○							
3	**Ventilation**	●	Windows (natural)	●	○			G			
4	**Control visual contact**	●	Parapet	○							
5	**Sound insulation**	●	Triple glazing	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	●	Heating/cooling pipe	●	●	E	–	G	●	●	○
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	– Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.21 Evaluation of the HDI-Gerling Headquarter

4.3.1.9 Case Horizon L’Oréal Headquarters

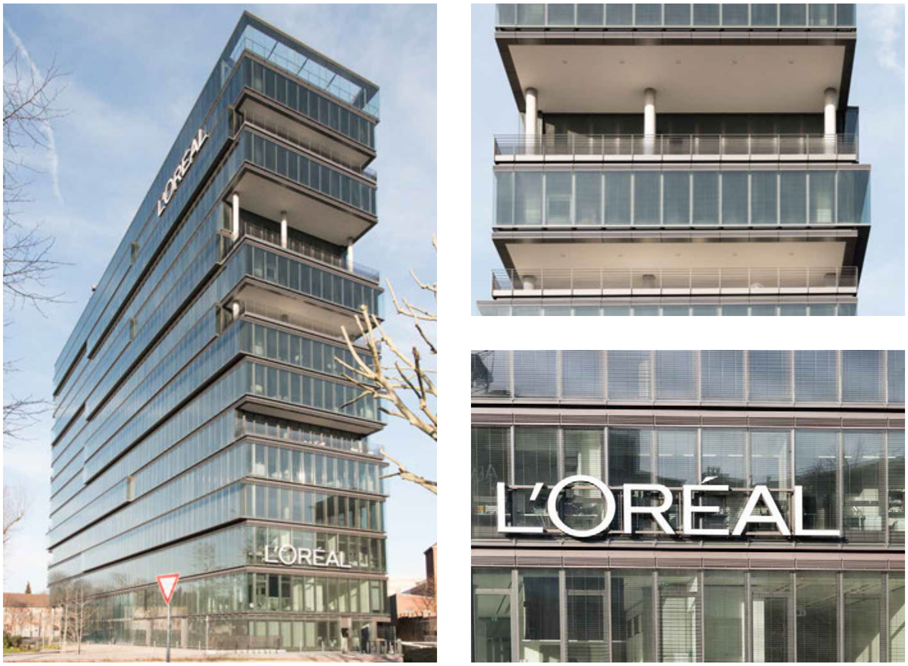

FIG. 4.22 Horizon L’Oréal Headquarters by HPP Architects

HPP Architects designed the Horizon L’Oréal Headquarters building in Düsseldorf and completed it in 2017 (FIG. 4.22). 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. 4.23, 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 (S. Heimann, personal communication, August 31, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	Sun shading lamellas	●	●	E	SEC	G	●	●	●
	Light deflection	●	Sun shading lamellas	●	●	E	SEC	G	●	●	●
	Glare protection	●	Blinds	●	○						
	Control daylight radiation	○									
2	**Thermal insulation**	●	Insulation glazing	○							
3	**Ventilation**	●	Window	●	○						
4	**Control visual contact**	●	Blinds	●	○						
5	**Sound insulation**	●	Glazing with foils	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	**—** Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.23 Evaluation of Horizon Lóereal Headquarters

TOC

4.3.1.10 Case Vodafone Campus

FIG. 4.24 Vodafone Campus by HPP Architects

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 (*Balance*, 2013). According to Heimann and as illustrated in FIG. 4.25, 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. 4.24, 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 used for lighting but for media projections on the building (S. Heimann, personal communication, August 31, 2018).

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		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	Sunshading lamellas	○							
	Light deflection	○									
	Glare protection	●	Blinds	●	○						
	Control daylight radiation	●		●	○						
2	**Thermal insulation**	●	Insulation glazing	○							
3	**Ventilation**	●	Window	●	○						
4	**Control visual contact**	●	blinds	●	○						
5	**Sound insulation**	●	Insulation glazing	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	○									
	De- / humidification	○									
	Electricity	○									
	Artificial light	○									
	Communication	○									

1 **Sun**	2 **Temperature**	3 **Air**	4 **User**	5 **Acoustic**	6 **Energy**	7 **Supply**
● Yes	**E** Extrinsic	**G** Gradual	**SEC** Seconds	**H** Hours	**M** Months	**–** Not available
○ No	**I** Intrinsic	**X** On-Off	**MIN** Minutes	**D** Days	**Y** Years	

FIG. 4.25 Evaluation of the Vodafone Campus

4.3.1.11 Case Capricorn house

FIG. 4.26 Capricorn house by Gatermann + Schossig architects

The Capricornhaus is located in Düsseldorf Medienhafen (FIG. 4.26). 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 (Fassaden, 2010). 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 (Weiss, 2010). 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. (2014), the façade also performs artificial lighting functions. Façade lights are integrated into the modules for this purpose. FIG. 4.27 shows the evaluation of the project based on the interview conducted with (S. Gaessler, personal communication, January 28, 2018).

		FULFILLED	TECHNOLOGY	FLEXIBLE	ADAPTIVE	OPERATION	RESPONSE TIME	DEGREE OF ADAPTABILITY	INPUT SYSTEM	PROCESSING SYSTEM	OUTPUT SYSTEM
1	**Solar shading**	●	Sun shading lamellas	●	●	E	–	G	●	●	●
	Light deflection	●	Sun shading lamellas	●	●	E	–	G	●	●	●
	Glare protection	●	Sun shading lamellas	●	●	E	–	G	●	●	●
	Control daylight radiation	●	Sun shading lamellas	●	●	E	–	G	●	●	●
2	**Thermal insulation**	●	Element facade	○							
3	**Ventilation**	●	Window	●	○						
4	**Control visual contact**	●	Element facade	●	○	E	–	G	●	●	●
5	**Sound insulation**	●	Window	○							
6	**Generate energy**	○									
	Store energy	○									
7	**Heating and cooling**	●	parapet	●	●	E	–	–	●	●	●
	De- / humidification	○									
	Electricity	●									
	Artificial light	●	Integrated lights	●	–						
	Communication	○									

1 Sun	**2 Temperature**	**3 Air**	**4 User**	**5 Acoustic**	**6 Energy**	**7 Supply**
● Yes	E Extrinsic	G Gradual	SEC Seconds	H Hours	M Months	– Not available
○ No	I Intrinsic	X On-Off	MIN Minutes	D Days	Y Years	

FIG. 4.27 Evaluation of the Capricornhaus

4.3.2 Cross case analysis

The cross-case analysis combines the data of the individual case studies into a holistic view. FIG. 4.28 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 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 function of humidification and dehumidification of the building. Only the façade of the Capricorn house provides artificial lighting for the building. The lighting technology found in some of the projects to provide for media installation is not considered in this compilation.

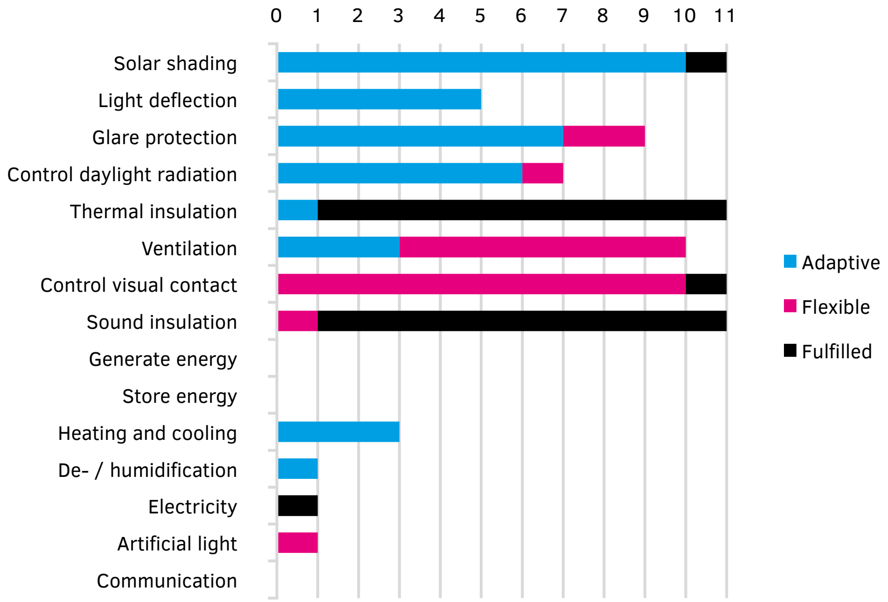

FIG. 4.28 Cross-case comparison of realised façade functions

The radial diagrams in FIG. 4.29 show which functions are jointly implemented. According to the colour scheme in FIG. 4.28, 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 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.

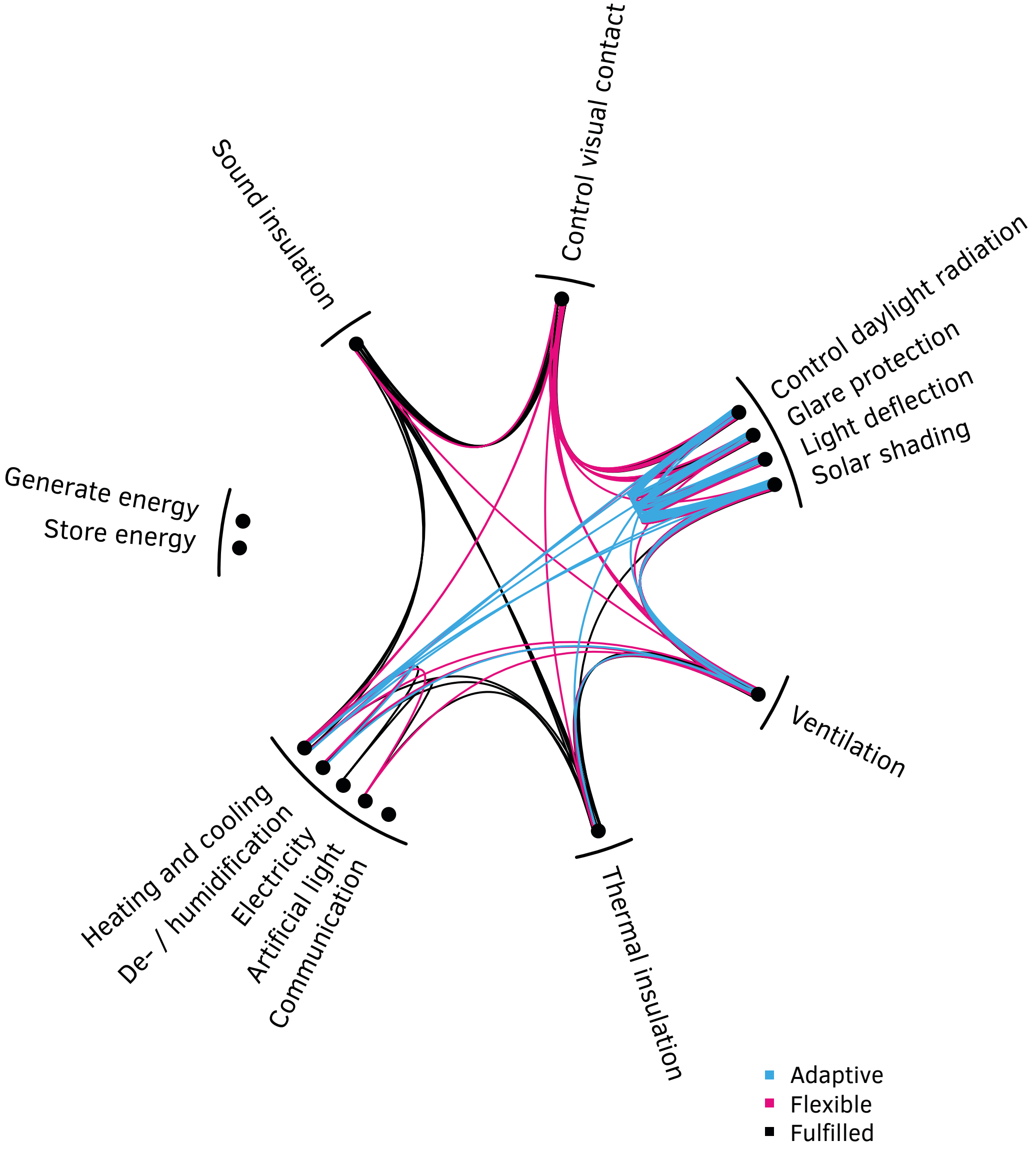

FIG. 4.29 Joint implementation of fulfilled, flexible and adaptive façade functions combined diagram on the left, and seperated by the individual categories on the right

FIG. 4.30 provides a differentiated view of the jointly fulfilled façade functions, also considering flexibility and adaptivity, organized according to the projects examined.

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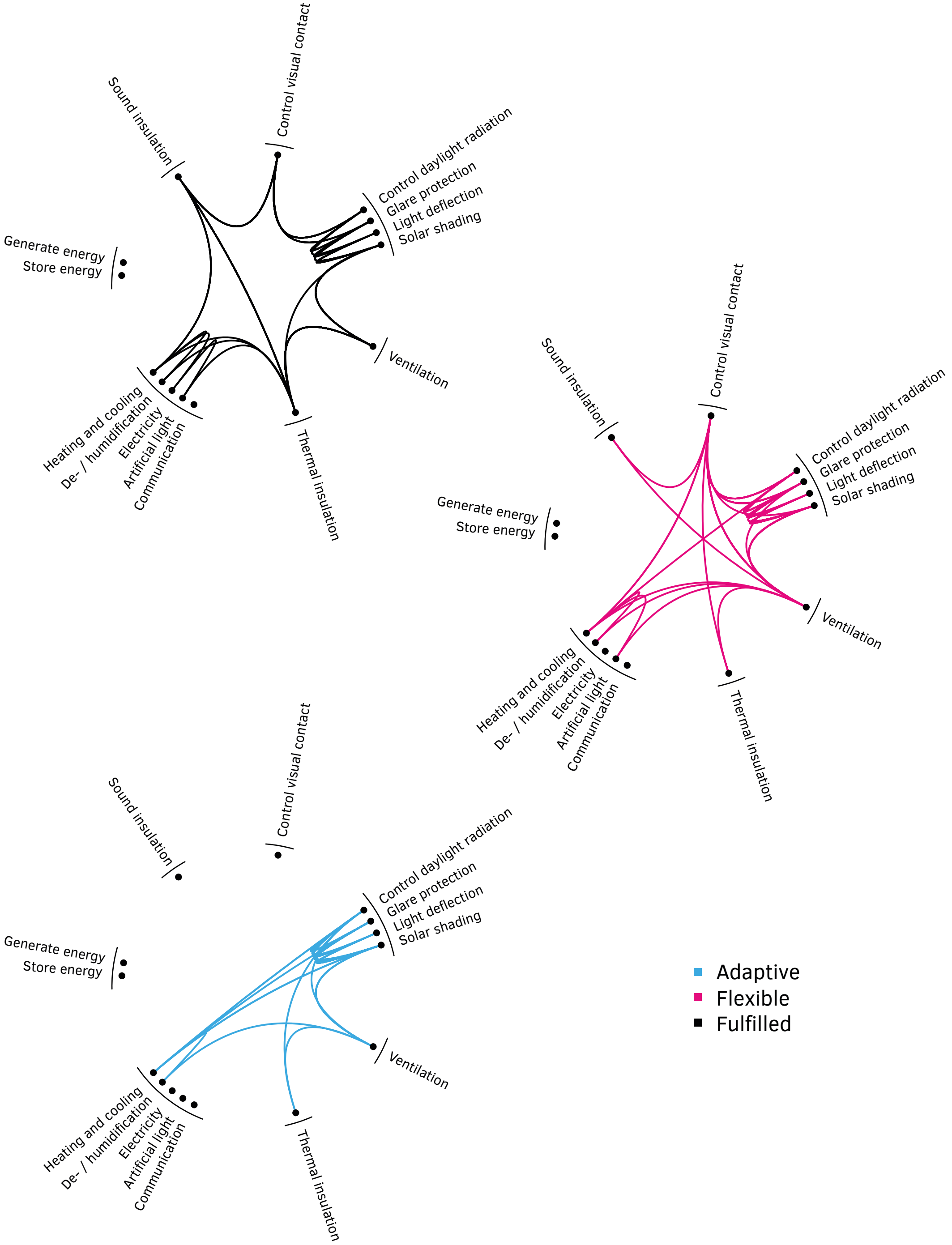

Sound insulation
Control visual contact
Control daylight radiation
Glare protection
Light deflection
Solar shading
Generate energy
Store energy
Ventilation
Heating and cooling
De- / humidification
Electricity
Artificial light
Communication
Thermal insulation
Sound insulation
Control visual contact
Control daylight radiation
Glare protection
Light deflection
Solar shading
Generate energy
Store energy
Ventilation
Heating and cooling
De- / humidification
Electricity
Artificial light
Communication
Thermal insulation
Sound insulation
Control visual contact
Control daylight radiation
Glare protection
Light deflection
Solar shading
Generate energy
Store energy
Ventilation
Heating and cooling
De- / humidification
Electricity
Artificial light
Communication
Thermal insulation
■ Adaptive
■ Flexible
■ Fulfilled

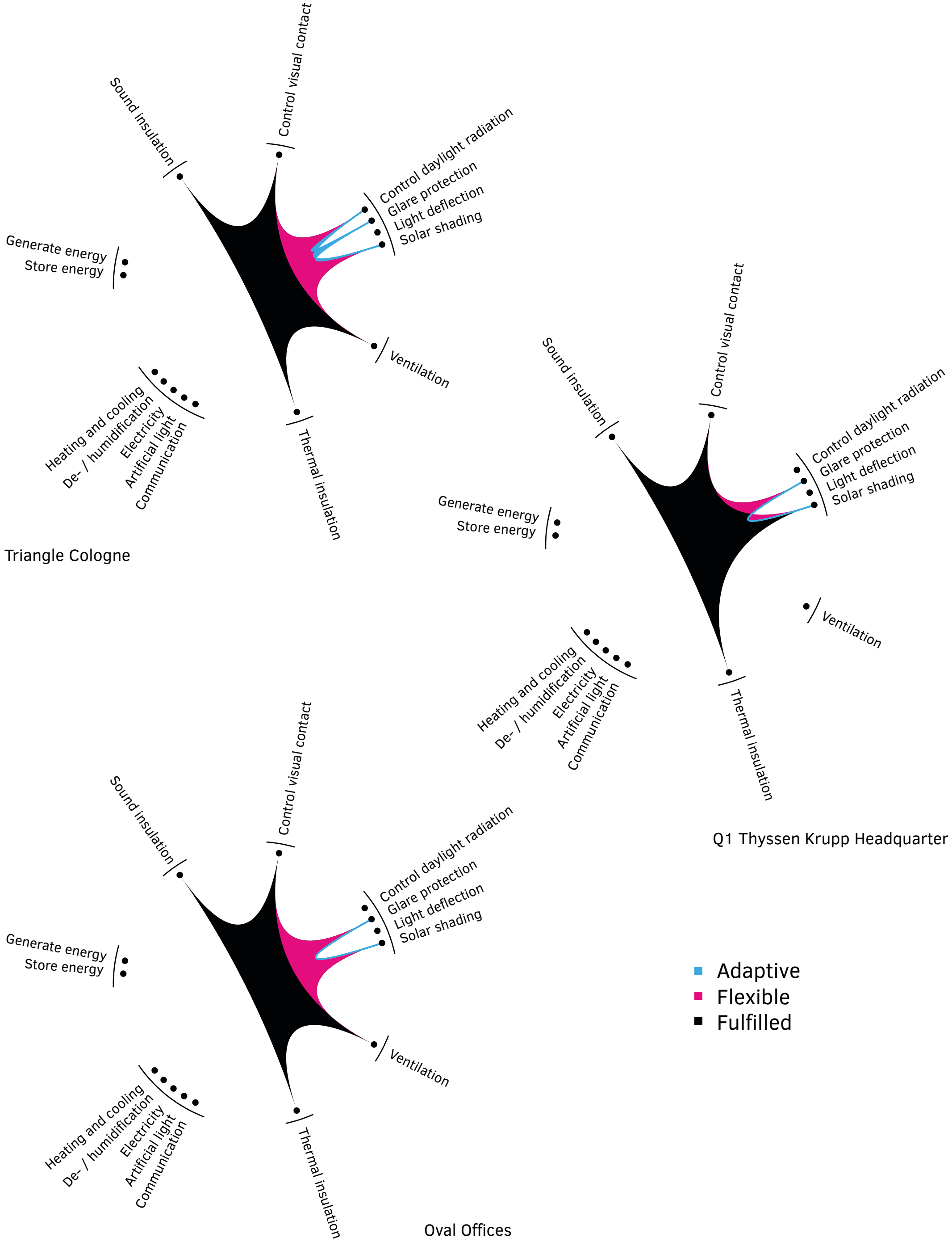
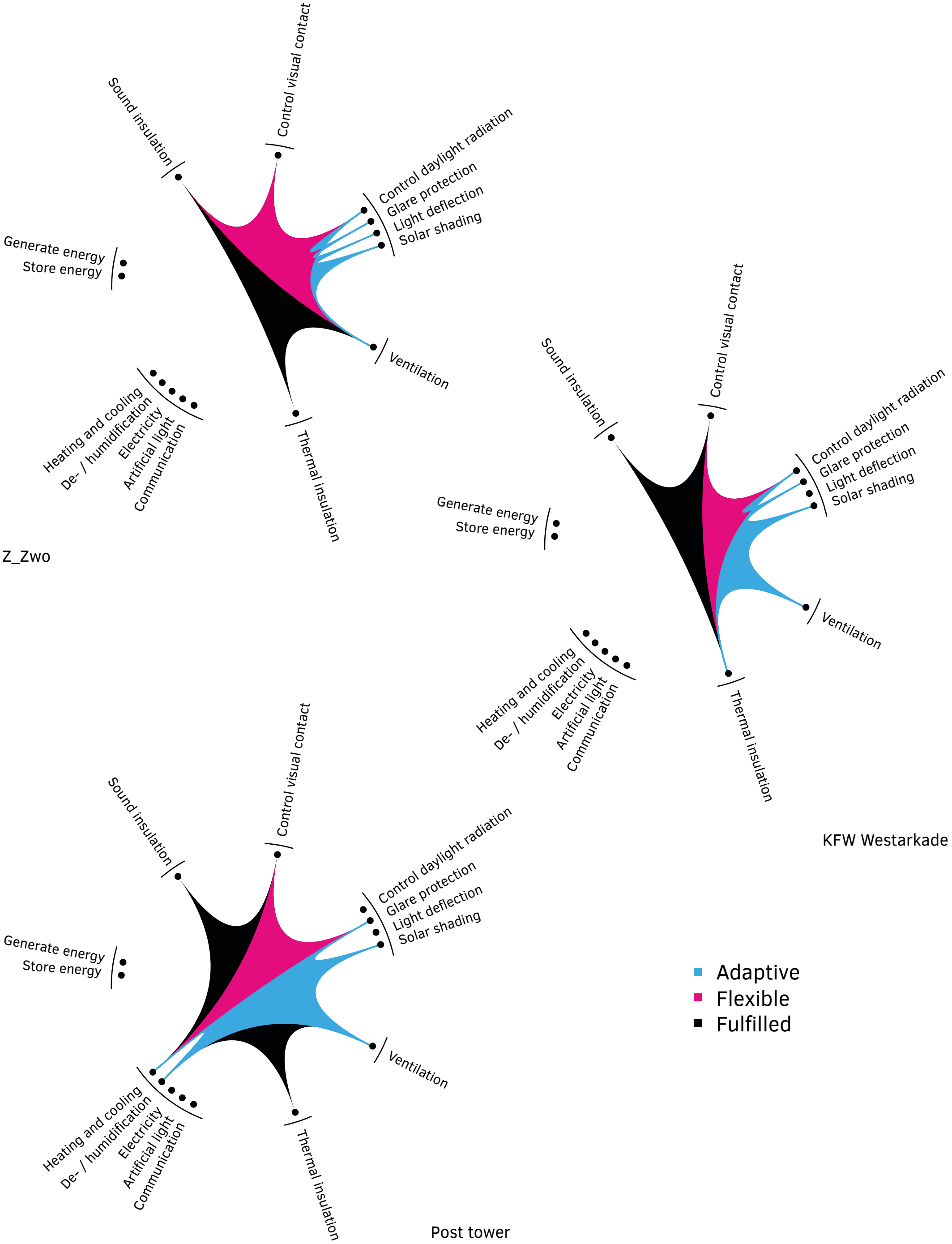


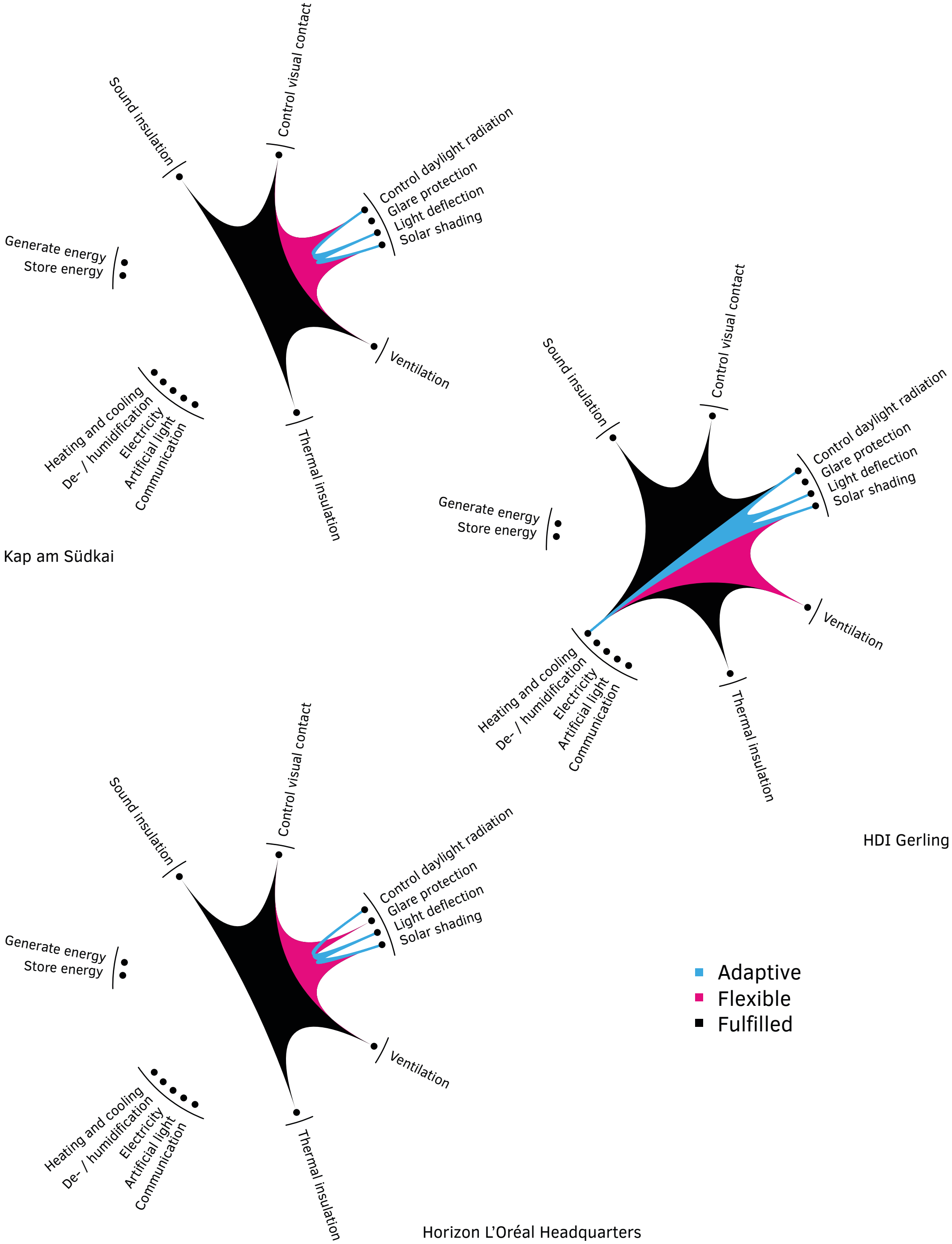
FIG. 4.30 Jointly implemented façade functions by project



Z_Zwo

KFW Westarkade

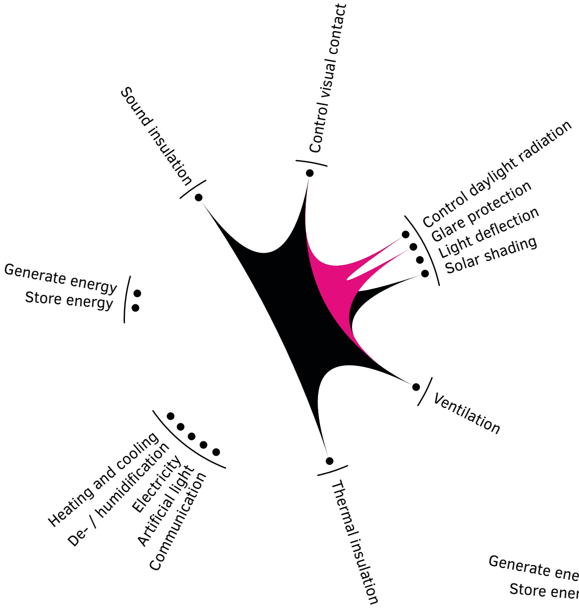
Post tower



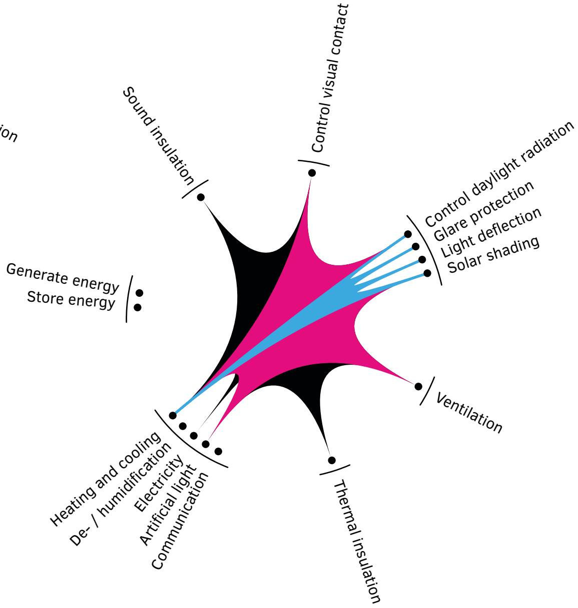
Kap am Südkai

HDI Gerling

Horizon L'Oréal Headquarters



Vodafone Campus



Capricorn house

🟦 Adaptive
🟥 Flexible
■ Fulfilled

None of the examined projects feature the application of smart materials. According to the definition by Loonen et al. (2015), the operation of adaptability is to be assessed exclusively as extrinsically. FIG. 4.31 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.

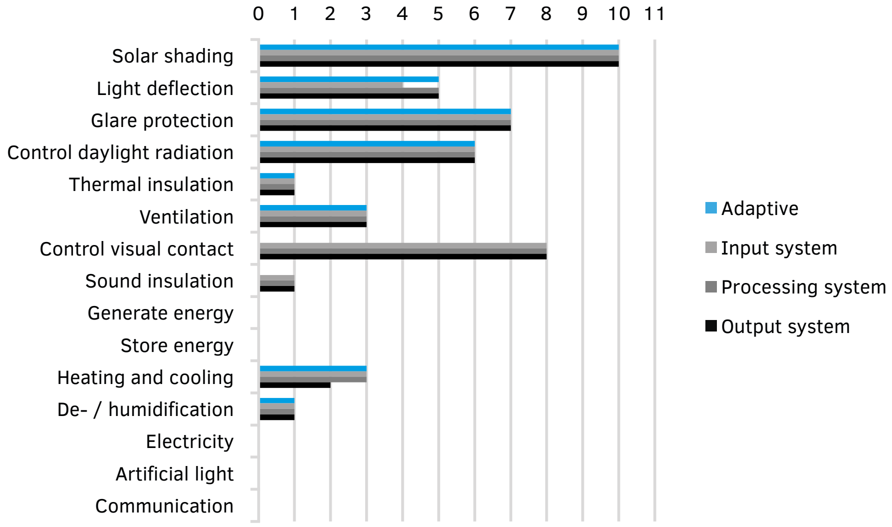


FIG. 4.31 Automation in the realisation of adaptive façade functions

The overview of the project data shows that there are different degrees of a decentralized 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. 4.32 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.

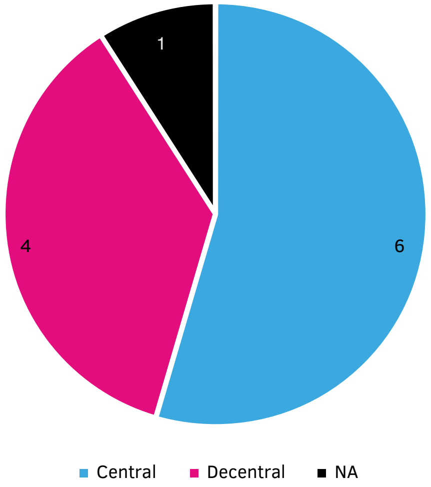


FIG. 4.32 Relationship between decentralized and central automation

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.

4.4 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 organized in more than half of the projects. Different organisational forms and intermediate stages of decentralized implementation were identified in the projects that have been assessed as decentralized by the interview partners. As described in the cross-case analysis in Section 4.3.1, the controls are often combined and bundled in units of different sizes. The distinction formulated by Loonen et al. (2015) 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 decentralization 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 façade functions, the automated components do not meet the requirement for intelligent cooperation, because they are not embedded as formulated by Wolf (2012).

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4.5 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 realised.

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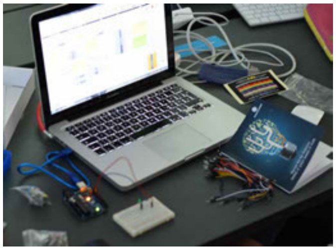
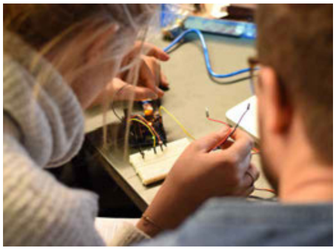
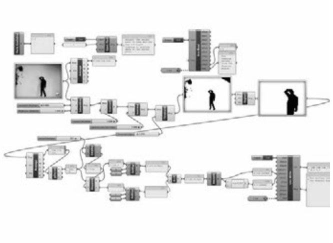
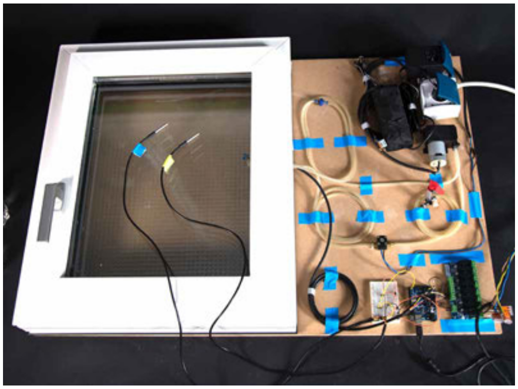
SIDE NOTE: **TEACHING MODULE - TECHNOLOGY AND DESIGN**

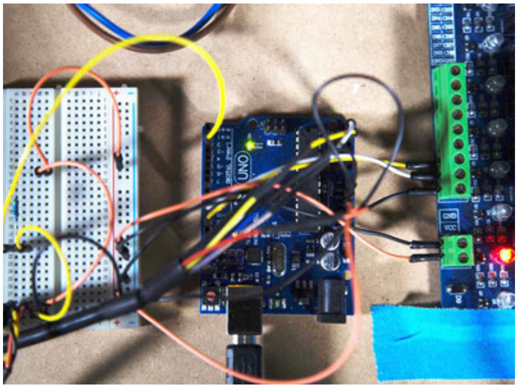
The project *ThinkingSkin*s benefited from the collaboration with students in dealing with automated design concepts. Jens Böke incorporated experience gained from working with the embedding of computing capacities in structural components of the building into teaching modules of the university curriculum. One example is the elective Master module Technology and Design at the Cologne University of Applied Sciences. Together with the students, concepts for intelligent components were developed on the basis of the Arduino platform (FIG. A and FIG. B). The control of adaptation processes was realized according to FIG. C via node-based programming in Firefly for Grasshopper. FIG. D and FIG. E show an example of a student project in which the thermal insulation of a glass window can be adapted by varying the pressure between the double glazing.


A Arduino starter Kit


B First circuits using breadboards


C Visual programming of the micro-controllers


D Student project on adaptive U-values through air pressure regulation


E Arduino based control of the compressor for pressure regulation

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Rear view of the developed cyber-physical façade prototype

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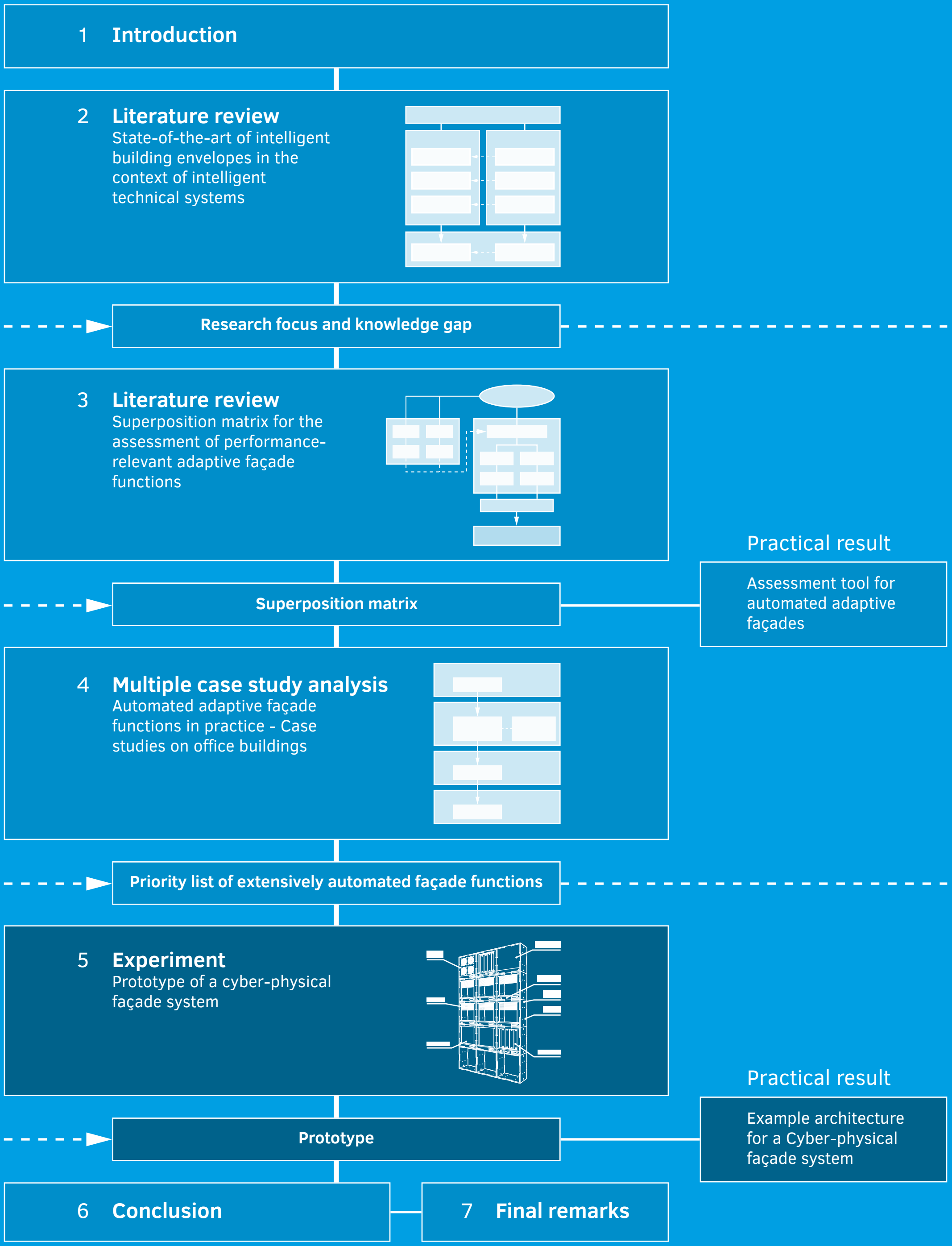

1 **Introduction**

2 **Literature review**
State-of-the-art of intelligent building envelopes in the context of intelligent technical systems

Research focus and knowledge gap

3 **Literature review**
Superposition matrix for the assessment of performance-relevant adaptive façade functions

Superposition matrix

Practical result

Assessment tool for automated adaptive façades

4 **Multiple case study analysis**
Automated adaptive façade functions in practice - Case studies on office buildings

Priority list of extensively automated façade functions

5 **Experiment**
Prototype of a cyber-physical façade system

Prototype

Practical result

Example architecture for a Cyber-physical façade system

6 **Conclusion**

7 **Final remarks**

5 Prototype of a cyber-physical façade system*

In the case study in Chapter 4, none of the investigated projects was identified as already cyber-physically implemented. However, with one exception in project 4.3.1.10 (Case Vodafone Campus), the basic application of automation technologies to the façade was recognized in all cases. Different façade functions are frequently and comprehensively implemented in an automated manner. Also priorities for the joint implementation of these functions become clear. Accordingly, the functions solar shading, ventilation and the building technology functions heating and cooling were determined to be particularly promising for consideration as active units in cyber-physical façades. It is unclear how these functions must be technically equipped and organised in the façade system in order to enable their cooperation following the model of networked industrial production plants. The first state of the art study found that cyber-physical systems can be defined on the basis of fulfilled characteristics. Thus, the technical feasibility of cyber-physical façades is investigated in a practical examination of the possibility of implementing identified characteristics. The following abstract provides an overview of the investigation carried out.

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* The chapter is based on a manuscript that was previously published as journal article: Böke, J., Knaack, U., & Hemmerling, M. (2020). Prototype of a cyber-physical façade system. *Journal of Building Engineering*, 101397. doi:10.1016/j.jobe.2020.101397

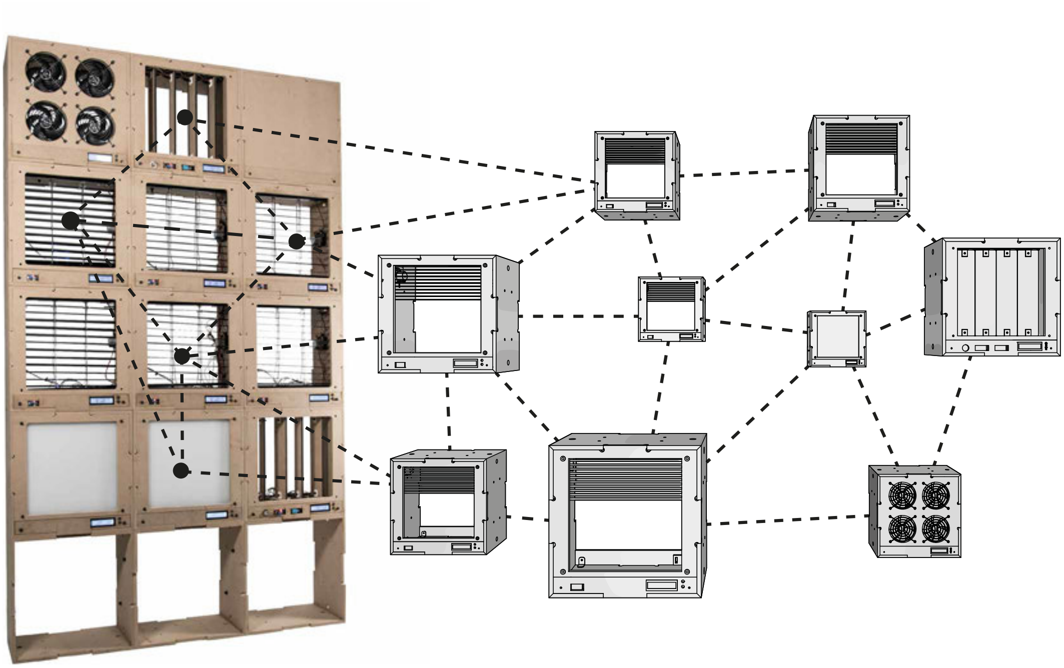

FIG. 5.1 Graphical abstract for the development of a prototype in the fourth investigation

The research examines the technical feasibility of façades as cyber-physical systems. Cyber-physical systems revolutionize former hierarchical and closed automation concepts of mechatronics by cooperating 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 criteria of cyber-physical systems to façades. The prototype is organized in modules, each of which represents one instance of the selected façade functions solar shading, natural and mechanical ventilation and heating and cooling. The emphasis lies on the development of a communication system that allows the functions to communicate and cooperate with each other. The 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 the embedded control, the integration of actuators and sensor networks, the implementation of a communication system and the connection to a digital twin are also feasible and promising in the façade domain.

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5.1 Introduction

5.1.1 Background

In the current digitalisation a transition towards ubiquitous computation and the comprehensive networking of our environment into an Internet of Things (IOT) takes place (Yaqoob et al., 2017). In this context, cyber-physical systems (CPS) are significantly changing the design concept of automated applications (Rajkumar et al., 2010). Due to very heterogeneous approaches in different fields of application, cyber-physical systems are not clearly defined, but described by possibly fulfilled criteria (Wang et al., 2015). 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, CPS are deeply embedded and decentrally organised (Brettel, Friederichsen, Keller, & Rosenberg, 2014; Monostori, 2014). 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 (2008), the networking of the components is a core aspect in the transformation of embedded systems into cyber-physical ones. Wang et al. (2015) 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. CPS operate in unpredictable environments. They must be reliable and robust in dealing with unexpected conditions (Lee, 2008).

Cyber-physical systems are already employed in many application domains. Examples are autonomous transport systems, smart energy supplies, and robotic surgery (Monostori, 2014). In 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 (Dumitrescu et al., 2012). The individual production assets of these systems exchange information via a machine-to-machine (M2M) communication network described by Xu, Yu, Griffith, and Golmie (2018) and Verma et al. (2016). 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. (2017) and Kritzinger, Karner, Traar, Henjes,

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and Sihn (2018), which enables both monitoring and optimization of production processes via digital simulations. The development of cyber-physical systems is also in industry still at its beginning. However, there are already methods and reference models for the design of CPS in this domain, like the level architectures introduced by Lee, Bagheri, and Kao (2015) and Herwan et al. (2018).

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 a highest possible efficiency. Façades constitute technical systems of different components and material layers. In the interaction of the components they fulfil the multitude of different functions, listed by Klein (2013). 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. Moloney (2011) and Loonen, Trčka, et al. (2013) call in this context 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, Knaack, and Hemmerling (2020), instead of using smart materials as described by Drossel et al. (2015) and Ritter (2007), façade adaptations are mainly carried out by the use of automation technologies. Especially in buildings with high proportions of glazing, automations 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 are implemented, including KNX, LonWorks, BacNet, ZigBee or Z-Wave (Domingues et al., 2016). 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. (2009). 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 to the industry for the implementation of cyber-physical systems in the field of façade applications. Böke et al. (2019) 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.

5.1.2 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 in principle be designed. 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.

5.1.3 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 (2012), 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.

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5.1.4 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 organised 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?

5.2 Methodology

5.2.1 General concept

The investigation is based on the experimental development of a modular prototype according to FIG. 5.2. The prototype consists of individual frame elements that are mounted together to form a complete system. The modularity illustrates the decentralized organization 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. (2019). 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 automated. Böke et al. (2019) identify the sun-related functions solar shading, glare protection, daylight control and light deflection, as well as ventilation, and the support functions heating

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and cooling. Since these functions are often implemented jointly automated in façades, 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 the ventilation is implemented as both natural and mechanical ventilation.

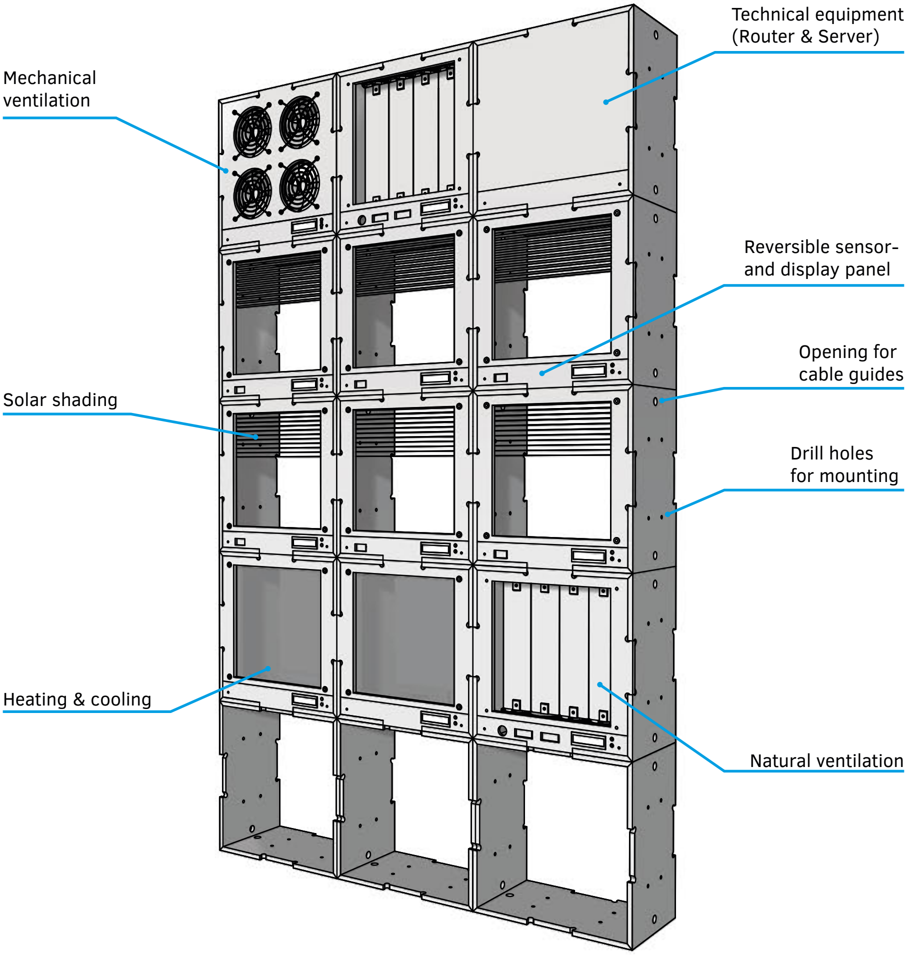

FIG. 5.2 Concept scheme based on a 3D- model of the cyber-physical façade prototype in Rhinoceros

The prototype is developed in the mindset of an ontology as described by Gruber (2009), which is not about the specific implementation of automated façade functions, rather than about their exemplary attributes and correlations. Although the prototype depicts the façade abstracted 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. In the middle section is the façade function sun protection realised six times. In the top level, two modules illustrate the mechanical and natural ventilation. In the selection and composition of the façade functions, care was taken 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 orients to the outside of the façade, while the building inside is represented by the opposite, open side (FIG. 5.3).

FIG. 5.3 The front of the prototype with visible sensors, LCD dsiplays and LEDs

5.2.2 Representation of the automated adaptive façade functions

The functions and their adaptation processes are visualised by 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 by the number of available components, sensors, actuators and libraries and 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 (2011).

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, also not all sensor data built into the system are used in the feedback loops in order to maintain the proportion between programming effort and significance of the investigation. In the collection of data, a distinction is made between sensors oriented to the outside and those oriented to the inside. Each module is embedded due to the integration of an associated NodeMCU V2 Amica micro controller as shown in FIG. 5.4. 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 WiFi 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.

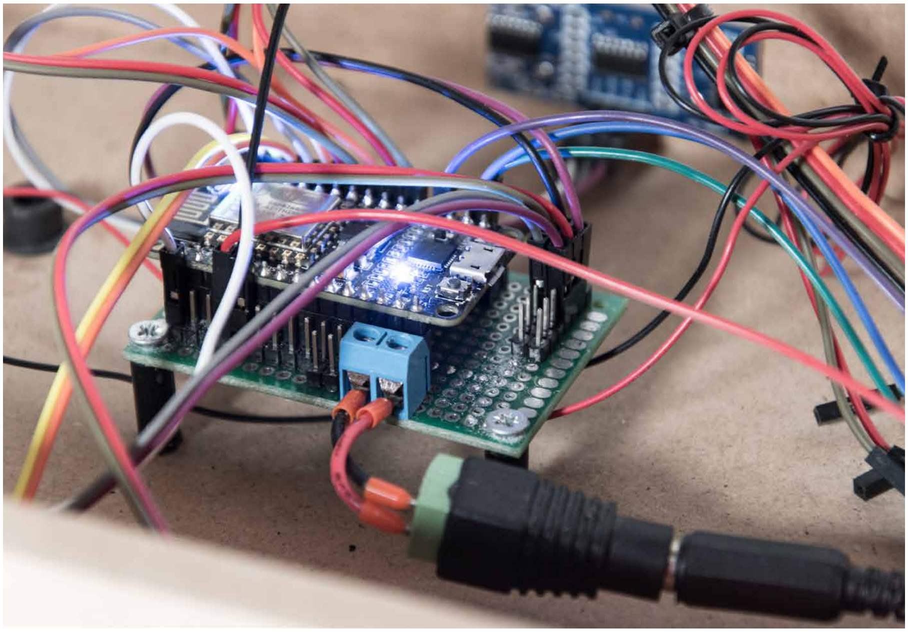

FIG. 5.4 Close-up of the NodeMCU V2 Amica micro controller installed on a circuit board

FIG. 5.5 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 to the mechanism of the blinds to enable the automated opening by the 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 Modules was omitted during the development process due to limited microcontroller connections.

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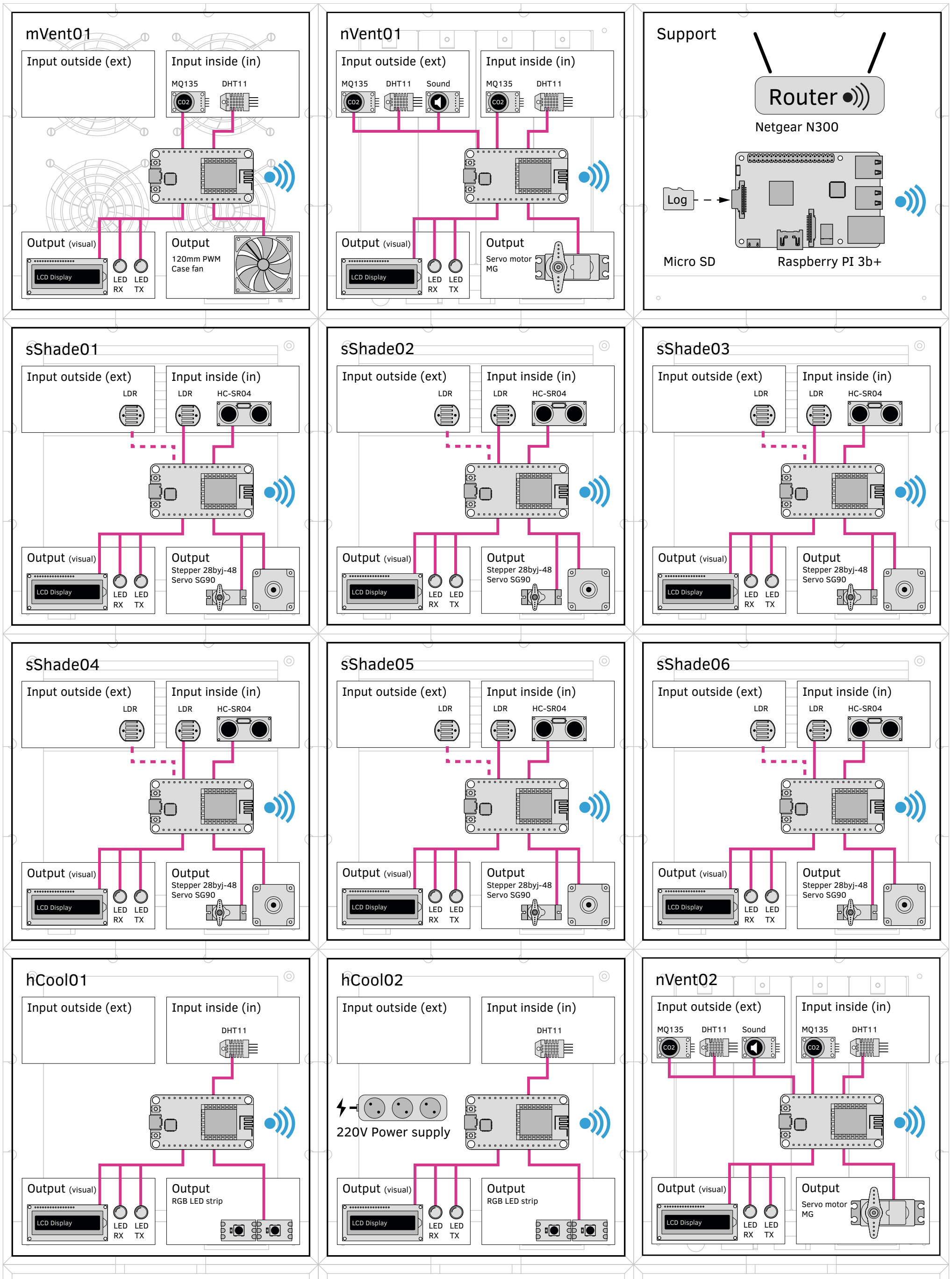

FIG. 5.5 Technical equipment of the prototype

Most sensors are installed in the natural ventilation modules. Temperature, humidity and air quality are measured both inside and outside. To the outside a noise sensor is installed. 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 120mm 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.

5.2.3 Modular and demountable design

Kaelbling (1987) defines modularity besides robustness and adaptivity 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.

5.2.4 Power supply

The modules are supplied with electricity by a central 5V / 20A 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 12V adapter. The microcontroller of the function is connected to this power supply via a step-down module.

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5.2.5 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 necessary for an internal system communication (Wang et al., 2015). In this study, a connection to the global Internet is neglected and wireless communication takes only place within the developed system.

Topologies describe the organizational 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. 5.6. 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.

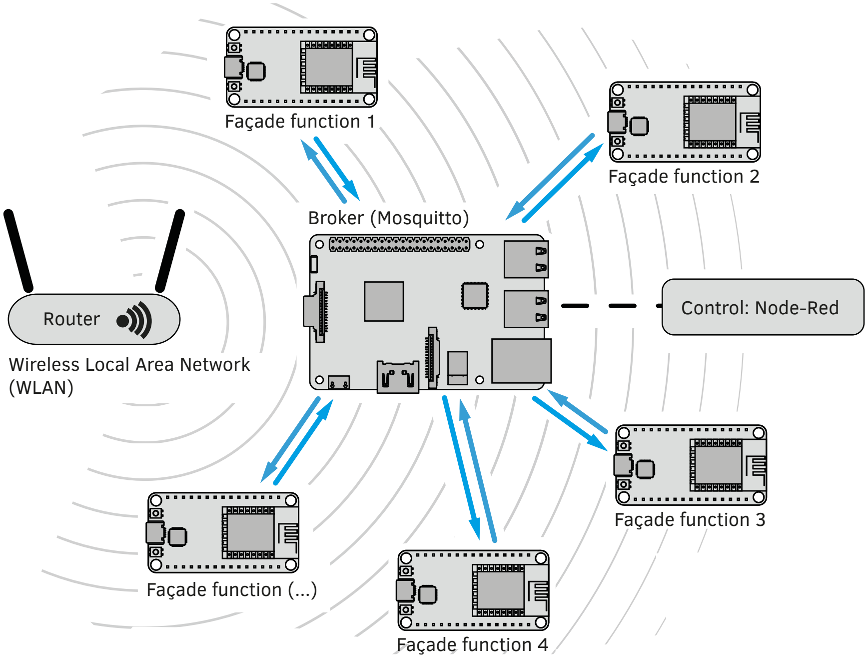

FIG. 5.6 Organization of the MQTT communication system derived from Joncas (MQTT and CoAP, IoT Protocols | The Eclipse Foundation, https://www.eclipse.org/community/eclipse_newsletter/2014/february/article2.php, (accessed November 11, 2019)

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 compared to other protocols two times faster (Çorak, Okay, Güzel, Murt, & Ozdemir, 2018). Three quality of service (QOS) levels are possible. Due to the 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 (Lee, Kim, Hong, & Ju, 2013).

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 over 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, in Section 5.2.6 described, feedback loops (*MQTT Version 5.0*).

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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 a flashing of the installed respective LEDs.

5.2.6 Control logic

The control of the prototype is organized in two levels (FIG. 5.7). The programming uploaded to the microcontrollers represents the lower control level as formulated by Dumitrescu et al. (2012). 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.

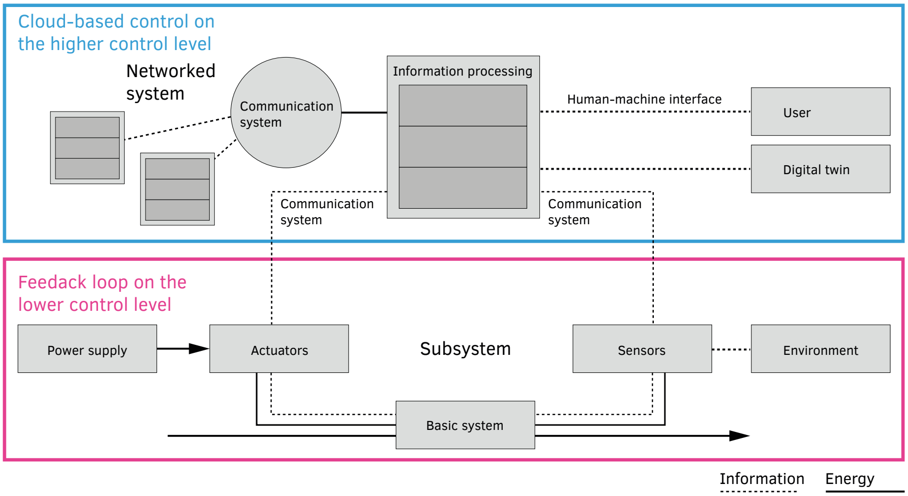

FIG. 5.7 Structure of the control strategy derived from Dumitrescu, Jürgenhake, and Gausemeier (2012)

5.2.7 Lower control level

The positions open, closed and half-open are possible for the flaps of the natural ventilation. 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 in 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, the 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 up-position. In addition, the three upper modules of the sun protection function were 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.

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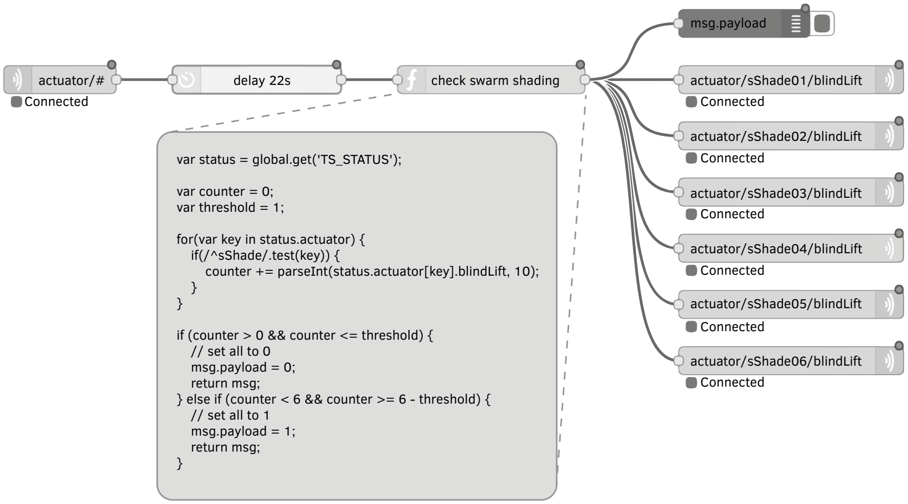
5.2.8 Higher control level

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 definition 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 as 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 over 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 links received information with the user interface, another flow stores all data in a log file and one more defines dependencies between the façade functions. The program can be used not only to process information from the system, but also to initiate 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 5.3. FIG. 5.8 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 the 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. 5.8 on the right, all sun protection modules are entered as recipients of the overwriting.



```
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. 5.8 Example flow comparing all solar shading adaptations to perform joint decisions

5.2.9 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 by 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.

5.2.10 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 (Negri et al., 2017). 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.

5.2.11 Evaluation

The successfully implemented characteristics of a cyber-physical system as formulated in the research questions in Section 5.1.4 is reflected by the demonstrable capabilities of the prototype. The prototype result and the communication of its façade functions is therefore evaluated qualitative and visual in five different functional tests. The tests were strategically selected to verify individual features. The first test evaluates with regard to sub-questions 1-3 the basic operability of the modules and the communication system. As examples of possible cooperation, the subsequent tests demonstrate the potential of an, in sub-question four addressed, internal façade communication. 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 Test 1 and 3 also consider the connection to a Digital twin formulated in the last sub-question.

Table 5.1 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 5.1. 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 Test 1 and 3.

TABLE 5.1 Protocol of the performed tests

Test #	Description	Test execution						Related video
		1		2		3		
		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

5.3 Results

The prototype was successfully realized, shown in FIG. 5.9 - FIG. 5.11. 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.

FIG. 5.9 Front view of the realized prototype

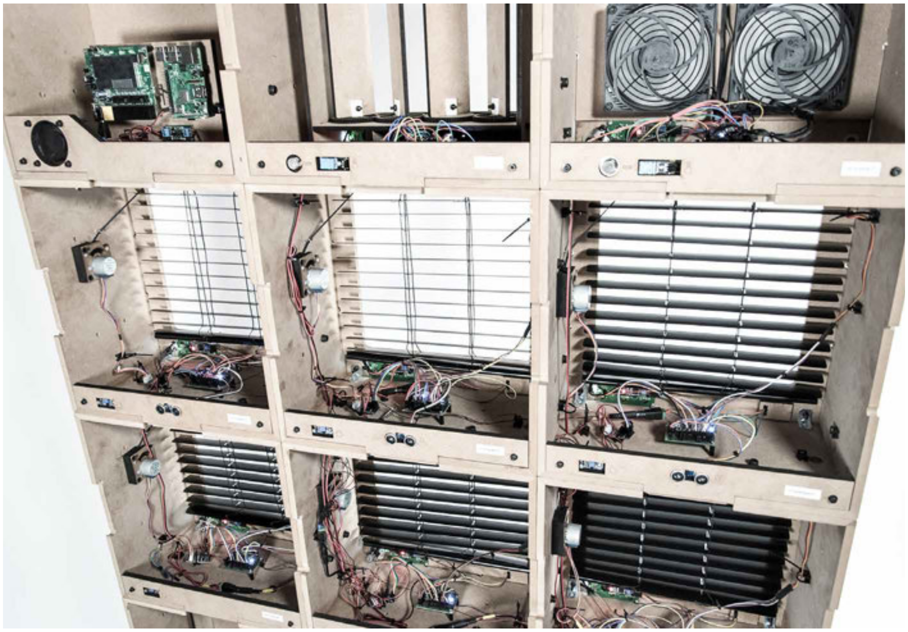


FIG. 5.10 Back side of the prototype with visible technical components

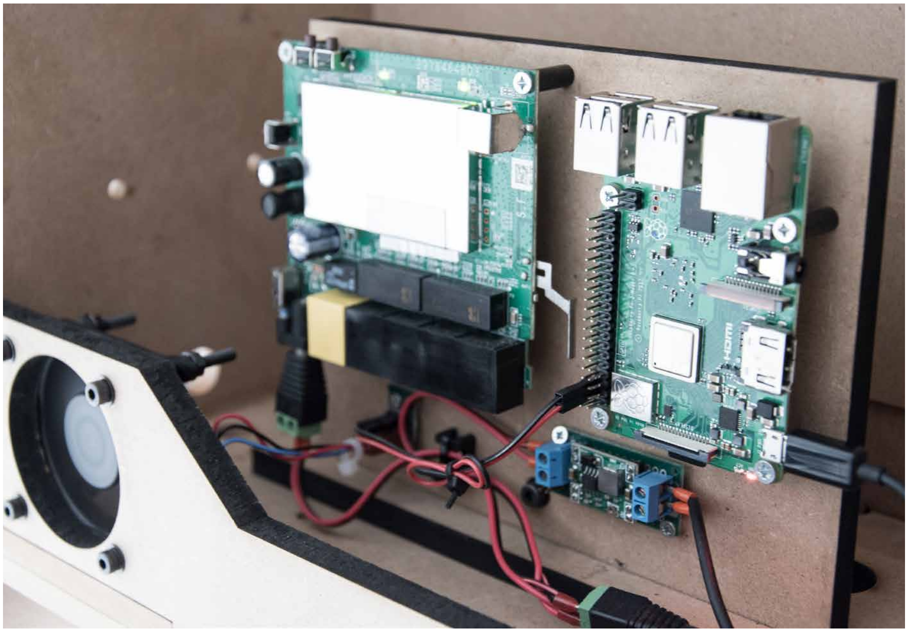
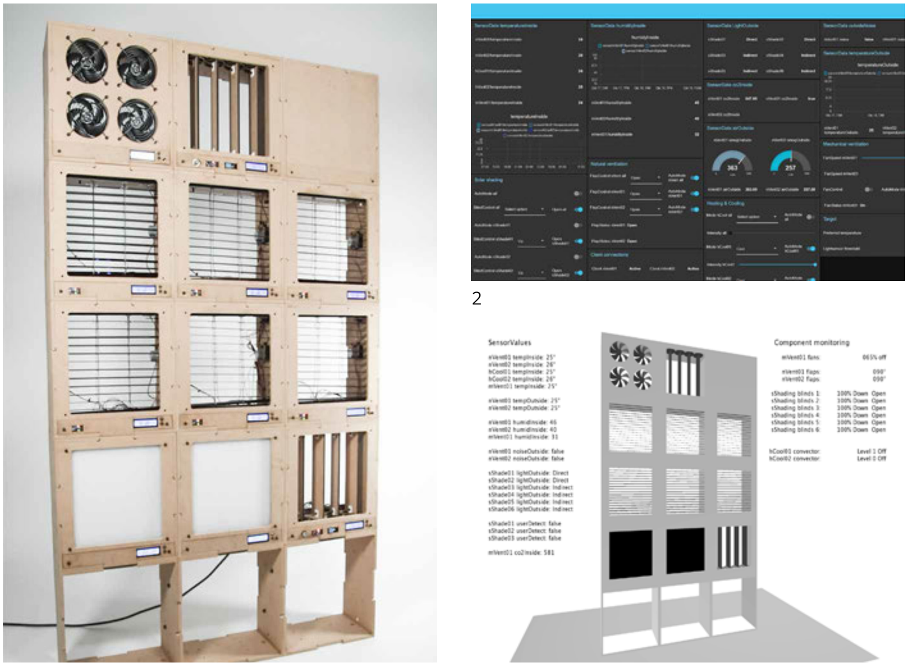


FIG. 5.11 Detail of the integrated Router on the left and the Raspberry Pi server on the right

5.3.1 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 video documentation as illustrated in FIG. 5.12 shows the physical prototype on the left, the user interface as 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 text-based and as a three-dimensional model. As result to the research-questions in Section 5.1.4, 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.



1

2

3

SensorValues

nVent01 tempInside: 25°
nVent02 tempInside: 26°
hCool01 tempInside: 25°
hCool02 tempInside: 26°
mVent01 tempInside: 25°

nVent01 tempOutside: 25°
nVent02 tempOutside: 25°

nVent01 humidInside: 46
nVent02 humidInside: 40
mVent01 humidInside: 31

nVent01 noiseOutside: false
nVent02 noiseOutside: false

sShade01 lightOutside: Direct
sShade02 lightOutside: Direct
sShade03 lightOutside: Indirect
sShade04 lightOutside: Indirect
sShade05 lightOutside: Indirect
sShade06 lightOutside: Indirect

sShade01 userDetect: false
sShade02 userDetect: false
sShade03 userDetect: false

mVent01 co2Inside: 581

Component monitoring

mVent01 fans: 065% off

nVent01 flaps: 090°
nVent02 flaps: 090°

sShading blinds 1: 100% Down Open
sShading blinds 2: 100% Down Open
sShading blinds 3: 100% Down Open
sShading blinds 4: 100% Down Open
sShading blinds 5: 100% Down Open
sShading blinds 6: 100% Down Open

hCool01 convector: Level 1 Off
hCool02 convector: Level 0 Off

FIG. 5.12 Extracted frame of the video documentation of test 1

5.3.2 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 FIG. 5.13. The test confirms real-time adaptations of the system formulated in sub-questions 4 and 5, including communication between the modules.

FIG. 5.13 The ventilation flaps close due to noise pollution and mechanical ventilation is activated

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5.3.3 Test 3 – Combined actions

According to the principle formulated in Section 5.2.8, also more complex coordination between the façade functions is possible. 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. FIG. 5.14 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 possible connection to a digital twin, which reflects the configuration and adaptations of the physical system.

1 2

FIG. 5.14 Combined adaptations

5.3.4 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 FIG. 5.15, 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.

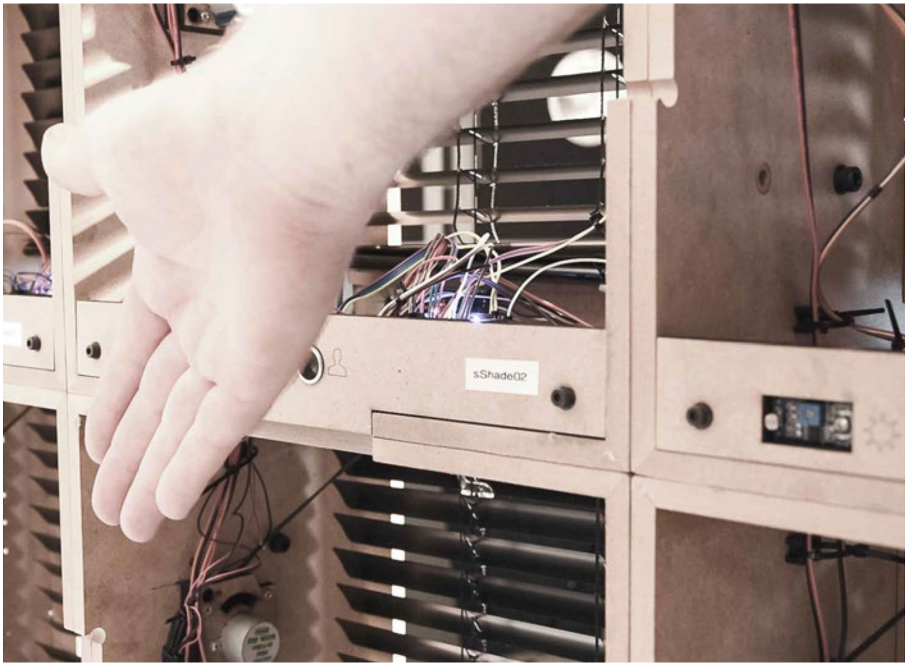

FIG. 5.15 Shared sensor information

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5.3.5 Test 5 – Collaborative decisions

Also, with regard to the fourth research question regarding a possible cooperation, the communication between the individual modules enables joint decisions. As an exemplary scenario, the total of six sun protection modules are exposed to direct sunlight. Covering the light sensor of one module 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. This occurs, as also visible in the video documentation, 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 (FIG. 5.16).

FIG. 5.16 Joint decisions between the modules

5.4 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.

The prototype nevertheless 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 foundation 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 levels and monitors the adjustment processes carried out, is also emphasized in this context. In line with the digital twins used in industry, a future optimization of the system by the 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.

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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 (2013) 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, Xie, Kuang, and Zhao (2012). 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 (*mppf - The multifunctional plug&play approach in facade technology*, 2015). The greatest possible flexibility in the configuration of the physical system could then be achieved by a self-sufficient, module-integrated power supply, for example via photovoltaics.

5.5 Conclusion

After the evaluation, the research questions of the study can be answered as follows: In 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 5.2.3. 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-question 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. In 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 sixth research question is possible and was implemented in the investigation due to missing software solutions, by a self-written program in the processing programming environment.

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Front view of the developed prototype

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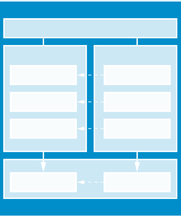
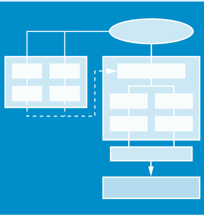
1 Introduction

2 Literature review
State-of-the-art of intelligent building envelopes in the context of intelligent technical systems



Research focus and knowledge gap

3 Literature review
Superposition matrix for the assessment of performance-relevant adaptive façade functions

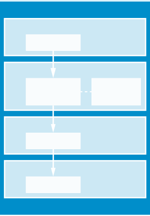


Superposition matrix

Practical result

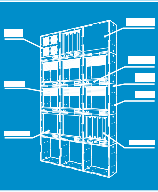
Assessment tool for automated adaptive façades

4 Multiple case study analysis
Automated adaptive façade functions in practice - Case studies on office buildings



Priority list of extensively automated façade functions

5 Experiment
Prototype of a cyber-physical façade system



Prototype

Practical result

Example architecture for a Cyber-physical façade system

6 Conclusion

7 Final remarks

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6 Conclusion

Each investigation in the research project *ThinkingSkin*s led to its own insights in the overall context of the project. This chapter discusses the findings from the executed partial studies and draws conclusions in view of the overall research question. An interpretation of the project's contribution to the topic of thinking skins, the acknowledgment of limitations, a reflection of the research impact and recommendations for future research are also part of this chapter.

6.1 Introduction

Under the guiding idea of a thinking skin, the project aimed at investigating the transferability of cyber-physical systems to the application field of façades. Four partial investigations were carried out to provide a comprehensive answer to the main question about how façades can be implemented as cyber-physical systems. They concentrate on the comparison with the existing role model of intelligent technical systems in the Industry 4.0, the consideration of relevant façade functions in a cyber-physical overall system, actual requirements and the technical preconditions in building practice as well as on the technical feasibility of such a system. Since the answer to the main question builds up on the results of the partial investigations, the first part of the conclusion concerns discussions and answers to the formulated sub-questions. They lead to a subsequent general conclusion of the research which is followed by a classification of the project in relation to the title *ThinkingSkin*s. In the following, recognised limitations and recommendations for future research tasks are provided. The conclusion section finalises with highlighting and assessing the project's scientific and social impacts.

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6.2 Answers to the research sub-questions

6.2.1 What are existing definitions and key aspects in intelligent façades and in intelligent technical systems?

The question was examined within the framework of a literature review. Both domains of intelligent façades and intelligent technical systems in the current understanding of the ongoing digitalisation were identified as active and not yet concluded fields of research. A main focus was on the investigation of existing definitions and related topics as well as on understanding the underlying state-of-the-art.

In the field of façades, it was not possible to determine a clear and universal definition of an intelligent system. Rather, the use of the term depends on the respective application and must therefore be individually defined. One observation is that the understanding of the concept of intelligence in construction has shifted with the time of its use. While the term was initially used primarily for the comprehensive mechanisation of buildings, it increasingly referred to physical abilities in the sense of an adaptive façade, which is why this term has prevailed. Many other keywords and terms, such as 'responsive', 'active', 'dynamic façades', have been identified and recorded in the literature search, which similarly address adaptivity. An important finding is that intelligence in the field of façades does not yet primarily refer to intelligent control. This is different to other application fields of intelligent systems in the investigated course of digitalisation. The term 'intelligent technical system' refers directly to the implementation of decentrally organised and cooperating production plants in the fourth industrial revolution. Intelligent technical systems are a specific application form of cyber-physical systems, which, due to their embedded computing capacity, enable close integration between physical systems and their control at the cyber level. Here, the intelligent control of a system including strategies of artificial intelligence, human-machine interaction and machine learning play a decisive role in the understanding of a system's intelligence. With the introduction of cyber-physical systems, definitions of intelligent systems are omitted, since the assignment of fulfilled criteria is more efficient due to the diversity in the various forms of application. The implementation of cyber-physical production systems follows the objective of increased flexibility and productivity in automated production processes.

With the understanding of intelligent systems, an associated state of development in the respective field of application becomes apparent. The application of cyber-physical systems to industrial manufacturing processes has enabled a new stage of development based on the decentralized organization of production facilities and their cooperation as an overall system. One reason for the research carried out in this doctoral thesis is that this development stage of intelligent systems has not yet been reached in the field of façade applications.

6.2.2 Which façade functions can be identified as possible parts of an intelligently networked façade system and which criteria can be used to evaluate their adaptability within such a system?

The question was addressed by a second literature review, in which a range of façade functions were identified as possible constituents of a cyber-physically realized façade. The investigation consisted of two sections. While the first section concentrated on providing necessary background information, the second part actually examined façade functions and their criteria for adaptive implementation.

The façade as a skin is understood as an active mediator between the external environment and the indoor climate of a building. For a holistic understanding of the façade and the evaluation of relevant individual adaptive functions, the influencing factors of the external boundary conditions and the aspects of interior comfort were first determined. Solar radiation, temperature, air quality, sound, wind, precipitation, and humidity were identified as central climatic influencing factors of the exterior. The requirements for interior comfort can be classified in the categories thermal comfort, aero & hydro-comfort, visual comfort, and acoustic comfort. The compilation of this information provided background knowledge for the actual selection of relevant façade functions and is understood as a possible indicator for the choice of sensors and actuators in the cyber-physical implementation of façades.

The implementation of an intelligently networked façade system requires an active role and cooperation capabilities of the façade functions operating within it. Therefore, relevant literature has been investigated to identify functions, which in automated and adaptive implementation, have an effect on the performance of the building. By consolidating and filtering existing listings, such as the façade function tree by Klein (2013), a total of fifteen façade functions in five categories were determined as possible constituents for cooperation in cyber-physical façades. In addition to sun-related functions such as sun and glare protection, they also include thermal insulation, ventilation, control visual contact and sound insulation. Additionally, support functions and energy generation and storage were identified as relevant.

A literature review has also been carried out to identify characteristics for the assessment of the automated adaptivity of façade functions. It was found that available literature refers to façades as overall systems and that different criteria are mentioned depending on the source. In the study, the different literature sources were combined and consolidated. As a result, nine characteristics were identified: general characteristics are the technology of the building components and their flexibility as well as the ability of autonomous adaptation. The behaviour is determined by the mode of operation, the response time, and the degree of adaptation. Evaluation criteria for automation are found in the three aspects of mechatronic systems, an existing input, processing and output system.

The result of the investigation is a superposition matrix in which the determined façade functions are assigned with evaluation criteria of their degree of automation and their adaptability. It has to be pointed out that this presents a theoretical consideration on the basis of the available literature, rather than information about the actual conditions in building practice. The test application of the superimposition matrix to a façade project confirmed that it can be applied for the purpose of a systematic investigation of a façade's degree of automation and adaptivity. The study comes to the conclusion that the superposition matrix can also be used as a practical tool for the design of cyber-physical façade systems due to the detailed breakdown of the active façade functions.

6.2.3 How and to what extent is automation applied to façades and which façade functions are taken into account?

The question is answered based on the conducted multiple case study analysis. Eleven realised façade projects were examined with regard to their automated and adaptive implementation in building practice. The developed superposition matrix served as an organizational tool for the differentiated evaluation of automated façades at the detail level of individual functions.

First, the investigated projects were evaluated independently in a single case analysis. The study concludes that in every examined case, if adaptations are realised, they are carried out by the application of automation technologies. Only one of the eleven projects was determined to be passive, without any automation

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technology being introduced. A general conclusion of the study is therefore that automation technologies are employed in most of the office façade projects realized today.

In the second part of the study, all collected data were combined and evaluated in a cross-case analysis. The focus was on the differentiated evaluation of automated façade functions and on recognising patterns in their implementation. In order to be able to answer the research question about which façade functions are subject to applied automations, those functions that were not considered at all in the investigated projects were excluded first. They include energy generation and storage as well as the infrastructure for communication. The support functions play a subordinate role in the investigated projects, only heating and cooling was identified as a relevant function in three cases. The functions exhibit solar shading, thermal insulation, sound insulation and the control of visual relationships were identified as regularly implemented and important façade functions, while the functions light control, glare protection and daylight irradiation control were implemented in about half of the investigated projects. In particular, sun-related building components are primarily implemented in an automated and adaptive manner. The characteristics of mechatronic systems were almost always found in the form of built-in sensors and actuators as well as a basically existing processing system. More than half of the projects are based on central control. In the projects classified as decentralized, different levels of decentralized control were identified, for example the bundled control of façade regions and individual elements. Even though a basic processing system exists, the embedding of computing capacities in the component of a façade function was not identified in all cases.

Since the cooperation of individual façade functions is an important feature of the cyber-physical implementation of façades, a special potential is seen in those functions that are often already implemented as a combination of automated and adaptive. Therefore, the cross-case analysis is also performed to determine patterns in the combination of automated and adaptive implemented functions. The study concludes that the sun-related functions: sun protection, glare protection, daylight radiation and light deflection are often implemented adaptive together with ventilation and the functions heating and cooling. Therefore, they are assessed as particularly promising for testing the technical feasibility of cyber-physical façades.

6.2.4 Is the construction of cyber-physical façade systems technically possible and how can such systems be designed?

In order to be able to answer this question, the prototype of a cyber-physical façade system was developed. The prototype is a first approximation in which important characteristics of cyber-physical systems were implemented. Different façade functions, such as sun protection, mechanical and natural ventilation as well as heating and cooling were considered. Within the prototype, individual frame modules each represent one instance of these façade functions. The modular structure relates to the decentralized organization of the system. By means of integrated microcontrollers, the façade functions represent embedded components that are additionally equipped with sensors and actuators. The cooperation between the façade functions was established via an MQTT based communication system. A digital twin illustrates the adaptation processes of the physical system in real time and is used for system monitoring. The digital twin also demonstrates the close interaction between the physical system and its digital control. Considering these successfully implemented features, the study concludes that cyber-physical façades are technically possible.

Answering the question of how such systems can be designed requires the consideration of both domains. On the physical level, the technical preconditions for decentralized cooperation between façade functions must be established. This requires the development of a system architecture that combines and organizes durable building materials with high-tech automation components. In the development of the prototype, this challenge was met with a modular and reversible system structure. Accordingly, the control of the system must be organized on the cyber level. Here, a key for decentralized cooperation of the façade functions lies in the separation of their local, embedded control and global, cloud-based management as well as in establishing a communication system. The design of the communication system is recognized as a key element of the cyber-physical façade, because if it fails, the cooperation between the functions comes to a standstill and they fall back on their own feedback loops. The inclusion of the digital twin was identified as a valuable link between the digital control and the behaviour of the physical system; it appears to be worth considering in the design of cyber-physical façades.

The evaluation of the prototype on the basis of five cooperation examples gives insight into promising capabilities of such façade systems. The possibility of direct relationships between individual façade functions and the ability of global parameters, to which all functions react while still following their own agenda, demonstrates a high flexibility of the system. As a result of the established communication it performs like an organism in a complex way according to globally formulated requirements. This is also reflected in the possible coordination of adjustments, in which deviations can be overruled from the collective of façade functions. The sensor data collected by each function is shared with the overall system. This is an advantage for the robustness of operation, as possible sensor failures can be compensated. At the same time, several sources of information can be compared with each other with regard to more accurate measurement results. Due to these identified opportunities, a great potential is seen in the implementation and further research of cyber-physical façade systems. The study comes to the conclusion that the realized prototype can serve as a template and reference architecture for this purpose.

6.3 Answers to the main question

The main question of the research project relates to the feasibility of façades as cyber-physical systems:

- **How can cyber-physical systems be applied to façades, in order to enable coordinated adaptations of networked individual façade functions?**

First it has to be noted that the current automated implementation of façades does not correspond to the characteristics of cyber-physical systems. Due to their predominant hierarchical system architecture and rule-based control, they represent mechatronic systems. The identified corresponding understanding of intelligent façades refers to the physical adaptability in the comparable understanding of adaptive façades. In view of current technological developments in digitalisation this requires a reorientation of the concept of intelligence, which should no longer refer to the physical façade system but to the intelligent behaviour by means of control on the cyber level. Before an estimation of how the application of cyber-physical systems to the façade can be achieved, it must also be concluded that an implementation of the façade as a cyber-physical system is generally possible. This finding is based, on the one hand, on the preconditions of existing automation concepts in façades found in the multiple case study in Chapter 4. On the other hand it is based on the successful implementation of decisive system properties in the development of a prototype, such as the embedding of façade functions, the implementation of a communication system and the connection to a digital twin.

The implementation of a cyber-physical façade system, following the model of intelligent technical systems in Industry 4.0, initially requires the identification of the constituents to be included. With an objective to increase the energetic performance, only those façade functions can be considered which also have an impact on it. Furthermore, only functions can be taken into account that are able to cooperate with each other in building operation due to their automation and adaptivity. The superposition matrix developed within the framework of the research project *ThinkingSkin*s provides an initial orientation for the selection of corresponding functions. A cyber-physical implementation of the façade is based on the decentralized organisation and control of the adaptive façade functions. Embedding computing power into façade components, outfitting them with sensors and actuators as well as implementing a communication system were identified as minimum requirements for the realization of a cyber-physical façade.

A system architecture is required which organizes the individual functions within the overall façade system. The prototype realized in this project provides orientation and can be used as reference model for the conception of such a system architecture. From the realization of the prototype it is possible to derive further planning tasks, which exist both on the physical and on the cyber level of the system: Physically, it requires the agreement of the construction principle with sensors, actuators, adaptive and embedded façade functions, as well as the integration of a network infrastructure. The challenge here is to combine durable building materials with more susceptible high-tech components. The modularity of the system implemented in the prototype provides a possible solution to this challenge. The development of a control concept represents a planning requirement on the cyber level. The focus lies on the definition of behaviour rules and an orchestration of cooperating functions. Against this background, one main conclusion of the project is that the key to the successful application of cyber-physical systems lies neither in a one-sided focus on physical abilities, nor in the prioritization of communicative and cognitive abilities in the sense of artificial intelligence on the cyber level. It is important to have a holistic understanding of the cyber-physical system that includes both domains in the planning. In this respect, the research project *ThinkingSkin*s provides a conceptual framework for the actual implementation and further research of cyber-physical façade systems.

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6.4 Retrospect on the project title TinkingSkins

With regard to the title, the question arises whether the project result also satisfies the concept of a *ThinkingSkin*. Section 1.2.2 identifies the architectural skin as an active mediator between the interior and exterior of the building. The cyber-physical implementation of the façade meets this requirement. The environmental boundary conditions and the established indoor climate are recorded by the extensive integration of sensors. The system is also able to react accordingly via the installed actuators and flexible components. The adaptation processes are carried out independently of the central control of a building automation system due to integrated microcontrollers. In this mode of operation, the system also meets the formulated expectation of autonomy.

While the conditions for an understanding as skin are therefore considered to be met, it is much more difficult to assess whether the cyber-physically realized façade is already a thinking system. In an understanding of machine thinking as formulated in Section 1.2.1 this question must be answered with ‘No’. Neither strategies of artificial intelligence nor machine or deep learning were applied in the control concept of the developed prototype presented in Chapter 5. The prototype operates on rule-based programming of the embedded microcontrollers and on the relationships established by the visual programming in the cloud. With regard to thinking, a more differentiated understanding of system autonomy is required. In building operation, the embedded façade functions operate autonomously without necessary user intervention and without explicit instructions from the central building automation system. However, the way the system works is based on global rules that need to be defined. Thus, the system as presented here needs supervision and requires an orchestration of cooperating façade functions. In addition to the assignment of collected sensor data, it is also necessary to establish relationships that determine which and how façade functions should communicate and cooperate with each other. An important design task therefore relates to the dependencies that determine the system behaviour of the cyber-physical façade. The basis for this is already established during the design of the system, because the selection of components and sensors creates predispositions and limitations that define the scope of the adaptability of the cyber-physical façade.

Because the cyber-physically realized façade has neither the ability for independent reasoning according to the model of the human brain, nor the ability to learn from the adaptation processes carried out, the superordinate goal of a thinking skin remains unachieved and continues to be a possible guideline for future research on intelligent façade systems. The present project makes an important contribution towards such systems. One key lies in the decentralized organization of the cyber-physical façade system, in which its behaviour is no longer determined hierarchically, but by negotiation of individual functions that form a network. As formulated in the definition of thinking in Section 1.2.1, a foundation for intelligent behaviour of a system lies in the interaction of simple processes. Thus, the cyber-physical implementation contributes to the intelligent operation of façades through the enabled cooperation of individual façade functions. The realized communication system is therefore understood as an important step on the way to a thinking skin. Also, organizationally, the cyber-physical implementation of the façade can be regarded as a pioneer for such systems. This is due to the close integration of the physical façade system with its digital control on the cyber-level. The identified artificial intelligence strategies depend on computing algorithms in cyberspace. Therefore, the cyber-physical implementation makes software and artificial intelligence related optimizations accessible for façades on the cyber-level . The digital twin, realized in the prototype development documented in Chapter 5.2.10, illustrates the close interaction between the physical and the virtual environment. It gives an outlook on future optimization possibilities, which will be digitally achieved with direct links to the physical system.

Even if the project does not fully reach the development stage of a thinking skin, the decentralized organization, the communication within the system and the virtual representation by a digital twin provide important characteristics of such a façade system. Cyber-physical façade systems are understood as drivers for innovations in the façade sector achievable today, and as a guiding idea for further investigation into thinking skins. An important contribution of cyber-physical systems for the development of thinking skins is the conceptual understanding that it is not sufficient to equip skins with cognitive abilities or vice versa to apply artificial intelligence to façades. According to the understanding of ‘cyber-physical’ as a unified concept, it requires a holistic understanding of the notion ‘thinking skin’ that seamlessly combines intelligent behaviour with physical adaptive capabilities. In this sense, both concepts correspond directly to each other. The analogy between thinking on the cyber level and the physical system implemented as a skin becomes clear in FIG. 6.1.

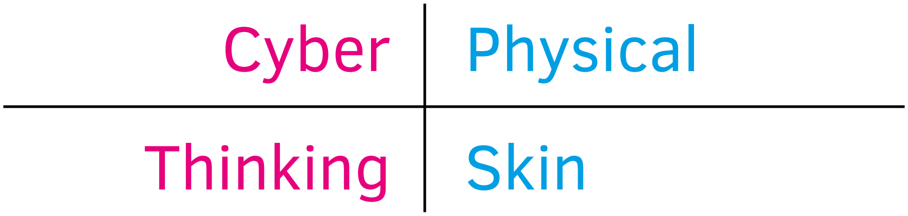

FIG. 6.1 Analogy between the concept of a cyber- physical system and a thinking skin

6.5 Research limitations

Different limitations have to be acknowledged resulting from the methods used to conduct the research. In approaching the topic of a thinking skin, decisions were made within the scope of the investigations, which finally led to the question of a possible transfer of cyber-physical systems to the façade. Against this background, it should be noted that this work represents only one perspective in the possible selection of many others.

A limitation lies in the restriction to the investigated reference model of intelligent technical systems in Industry 4.0. It can be expected that the consideration of further fields of application would have provided alternative and complementary characteristics of cyber-physical systems, which were not covered in this study.

The superposition matrix developed in Chapter 3 is not understood to be complete. Within the project it served as a tool for the systematic identification of promising façade functions for the experimental development of a cyber-physical façade system. The restriction of the superposition matrix does not mean that there are no further functions that may be relevant for the implementation of cyber-physical façades. In view of project dependencies and a possible future extension of the functional scope of façades, it presents only a first orientation that can be supplemented and adapted in the course of future research and application.

In the case study analysis in Chapter 4, eleven façade projects were examined. Their generalization represents a limitation since only projects in Germany were investigated. Reasons for this restriction were a feasible scope of work and the accessibility of project information. An uncertainty lies in the assignment of façade functions to individual components of the examined façade. Often, there is a grey zone in which one component fulfils several functions, or vice versa, the fulfilment of one function is distributed over several components. Therefore, possible interpretations represent a limitation. In the interviews conducted, the experts were asked for their assessment of whether the examined façade project was based on a centralized or decentralized control system. In retrospect, a more detailed query would have made sense, questioning the embedding and existing coordination of a function with other functions of the system. In its current form, the survey provides only a superficial assessment of a possibly already established decentralized organisation of the systems.

The prototype represents the principle system architecture of a cyber-physical façade abstracted and in model scale. A limitation is the neglect of actual conditions of the building construction, such as the use of real façade products and materials. In addition, the evaluation of the prototype is performed visually and qualitatively, without consideration of real climatic outside and inside conditions. The focus of the prototype development was on proving that façade functions are basically able to cooperate according to cyber-physical production systems in Industry 4.0. This was realized in the experimental approach by using a central router and a central server. In the implementation of façades as cyber-physical systems, a mesh-based architecture according to Yu, Kin-Fai, Xiangdong, Ying, and Xuyang (2017), in which the individual microcontrollers provide themselves with internet functionality and communication infrastructure would be more flexible and robust. Such a structure was both technically and conceptually beyond the scope of the project.

6.6 Future research

Extensive further research is required on the way towards actually implemented cyber-physical façade systems in building practice as well as in the pursuit of the superordinate goal in the development of a thinking skin. Several approaches for future tasks were identified during the development of the project. An overarching finding is the necessary integration of different fields of knowledge in further investigations. Due to the cross-domain nature of cyber-physical systems, interdisciplinary expert knowledge is required from various research fields, such as from information and communication technologies, cognitive sciences, cybernetics, electrical engineering, building automation systems and from façade design and engineering.

As formulated in the conclusion, the project provides a first conceptual framework. The result does not yet represent a design methodology for the implementation of cyber-physical façade systems in building practice. Further research is needed to identify necessary construction principles of such façades and approaches to their design. The same is true for understanding the actual impact of such buildings on the overall building performance. The expectation of energetic performance increases is derived from the positive effects achieved by the use of cyber-physical systems in the reference field of intelligent technical systems in Industry 4.0. It is important to acknowledge that the study does not yet provide evidence of the actual impact on the energy performance of buildings. A future task therefore lies in required energy simulations and measurements. Promising approaches for the energetic assessment of adaptive systems already exist (Attia et al., 2018; Loonen et al., 2017).

Humans need to be acknowledged as an important aspect in the consideration of applied technologies as presented in this project. A differentiation of possible roles appears important: On the one hand, that of humans as designers and administrators of cyber-physical façade systems. Furthermore, in taking part of the system by interacting and communicating with it. Last but not least as users of the building who are confronted with the perception of adaptation processes and the comfort achieved with the effects of the cyber-physical façade system. Due to the focus of the *ThinkingSkin*s research project on the general feasibility of such systems, the interrelationships and effects on humans were outside the scope of the study. A need for future research is therefore seen in human-centred approaches that might also profit from other knowledge fields, such as sociology or human-machine interaction in robotics. In addition to operational issues, ethical questions arise in view of the increasing autonomy of intelligent façade systems. Research is needed to define boundaries between personal freedom and meaningful restrictions of users.

The possible use of smart materials for executing adaptive façade functions was neglected in this project. The reason for not taking them into account was the closed nature of corresponding chemical or biological adaptation processes. Therefore such implementations cannot be programmed and considered for communication in cyber-physical systems. These requirements can change in the light of current and future research, and smart materials may then become an interesting aspect in such systems. A possible approach might be in bio-synthetetic systems as documented in 'Everything under control' (2013).

The digital networking of façade functions to cyber-physical systems represents a security risk that has already been addressed in many application fields of such systems (Zacchia Lun, D'Innocenzo, Smarra, Malavolta, & Di Benedetto, 2019). Wireless networking offers great flexibility for the implementation of cyber-physical façades, as the infrastructure of cables is eliminated and the system can be expanded and configured as required. At the same time, such an implementation, especially when connected to the global internet, is a gateway for hackers and cyber-attacks. Granzer, Praus, and Kastner (2010) determine the actual need for security concepts in building automation. It is expected that the risk will further increase with extensive automation and networking in the course of the cyber-physical implementation of façades. The building as a shelter with direct effects on the well-being of humans is understood as a particularly sensitive application field of cyber-physical systems. System security and strategies of threat prevention were beyond the scope of this work but recognized as a relevant topic for further research.

The *ThinkingSkin*s research project firstly focuses on the cyber-physical implementation of façades. However, building envelopes are only one partial aspect of buildings. A global view of cyber-physical buildings, which also take other aspects such as the integration into the general building automation system and the increasingly automated interiors of smart homes into account, remains as a future research task. Due to the holistic approach, which considers the entire building across all phases, building information modeling as described in Section 1.3.1 is identified as a possible approach to the development of comprehensive cyber-physical buildings. While the aspects mentioned above formulate basic research directions, the following recommendations refer to actual challenges in the implementation of cyber-physical façades. The identified research tasks result from the findings of prototype development. Thereby the lack of planning tools for the design of cyber-physical façades and their adaptation strategies was identified. In addition to the physical configuration of the system, these should also be able to map the changing states of the construction as well as the behaviour and communication of the system. The development of planning tools is considered an important research task to make the behaviour of the cyber-physical

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system predictable and to enable decisions on adaptation strategies in the early design phase of a project. Besides new planning tools, the extension of existing solutions such as Rhino Grasshopper 3D or Revit Dynamo, with tailored features for cyber-physical façade systems, is conceivable. The inclusion of design tools for the implementation of digital twins appears important. Corresponding programs, which are already available in the industry, do not exist in the construction sector. It remains open whether the future lies in professional and commercial software solutions or in individual programming tailored to the respective project application. In the implementation of the prototype, communication between façade functions was established via an MQTT-based publish/subscribe solution. The broker is the central interface through which all messages of the system run. If the broker fails, the communication breaks down and the façade functions fall back on their feedback loops. Therefore, the application of more robust communication systems is recognized as a future investigation goal. The implementation of mesh networks as described by Yu et al. (2017) or the proposal of distributed brokers as formulated by Kawaguchi and Bandai (2019) appears promising in this context.

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6.7 Research impact

The research project *ThinkingSkin*s is situated at the interface of adaptive façades and cyber-physical systems. Both knowledge fields are subject to current research, which has not yet been concluded. The relevance for the research on *ThinkingSkin*s derives from its function as a gateway, through which the knowledge obtained can be used in either direction. This applies both for the consideration of cyber-physical systems in the implementation and research of adaptive façades and for the development of new domains in the research and application of cyber-physical systems. The following sections provide an independent assessment of the societal and scientific relevance of the study.

6.7.1 Societal relevance

The research contributes in different ways to the treatment of current societal problems and questions. The coordination of mutually supporting and competing automated façade functions offers optimization potential for the performance of façades and thus for the energy efficiency of buildings. In this way of thinking, a cyber-physical implementation of distributed cooperating façade functions contributes to the formulated climate goals and the conservation of resources. At the same time, the availability of cyber-physical systems in the course of ongoing digitalization opens up new technical possibilities that cannot be used efficiently due to a lack of design methods and missing experiences in their application. For the domain of façades, a design foundation of such systems is established by reviewing existing requirements and the current conditions in building practice. Corresponding first experiences are supplied from the development of a prototype, which at the same time serves as a role model for the design of cyber-physical system architectures. In addition, the project contributes directly to the design of cyber-physical systems in building practice by providing usable results as, for example, the filtered compilation of essential façade functions in a superimposition matrix. By assessing the application of cyber-physical systems, the research makes an essential contribution to new innovations in the façade sector, which, according to the investigated role model of Industry 4.0, can lead to advanced products as well as to new business models.

6.7.2 Scientific relevance

An important scientific contribution lies in the knowledge transfer from the research of cyber-physical systems to the field of adaptive façades. Here, the study adds to the existing knowledge and responds to the demand for the development of holistic adaptive façade systems as formulated by Loonen, Trcka, et al. (2013) and Moloney (2011). A particular contribution lies in the provided knowledge about possible networking and interaction of adaptive façade functions by establishing communication within the framework of a cyber-physical overall system. The close integration of the physical system of the façade with its control on the cyber level enables the further application of current scientific fields like machine-to-machine communication, artificial intelligence or machine learning. Many identified research projects in the field of building automation and adaptive façades are starting with the available technologies whose application to architecture is being examined. This approach is reversed by the previous investigation of requirements in the scope of adaptive façades in Chapter 3 and by the investigation of actual conditions in building practice in Chapter 4. Accordingly, one contribution lies in the change of perspective, which leads to new insights and creates a conceptual basis for the future research of new automation technologies applied to the façade.

Detail of the energy supply of the prototype

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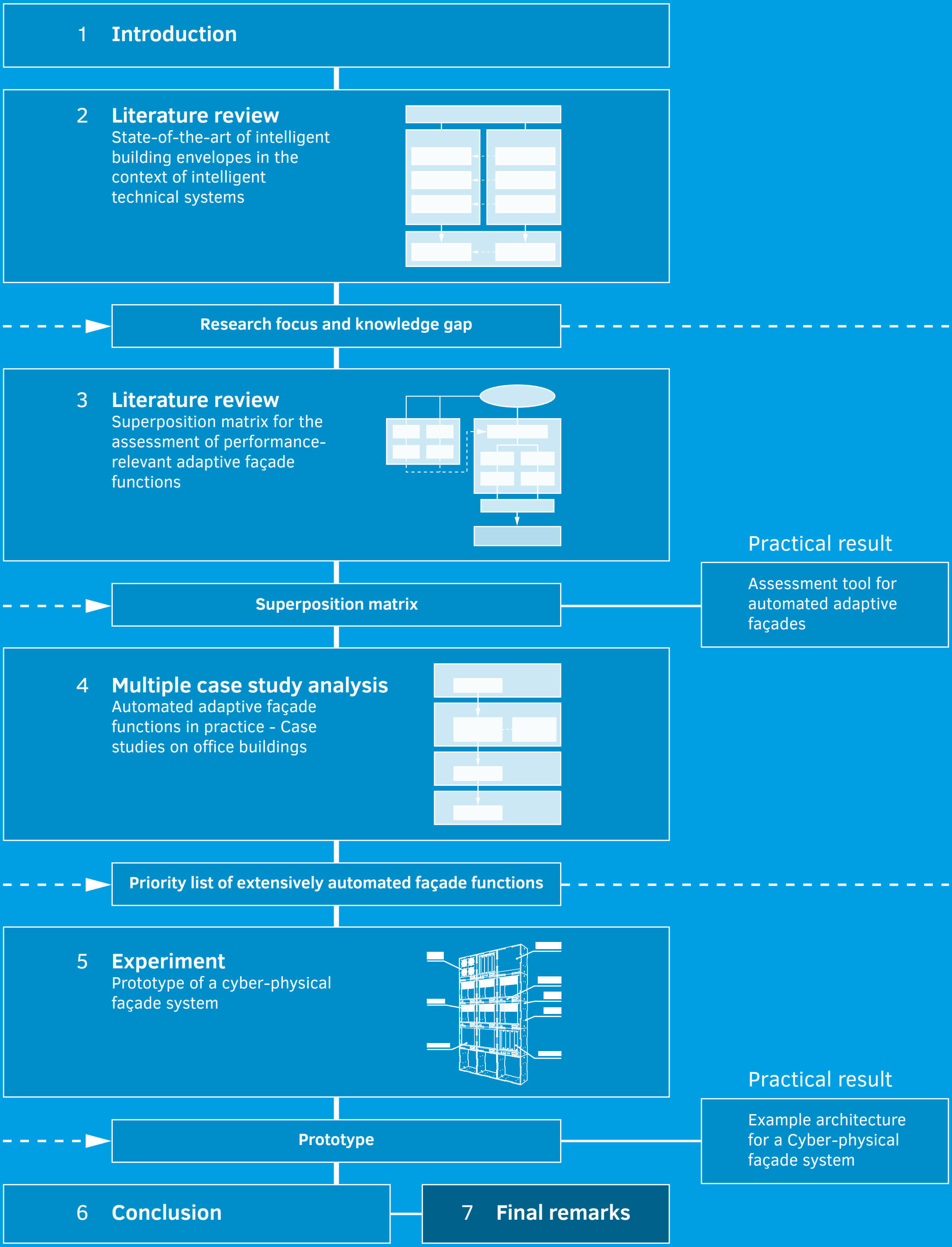

1 **Introduction**

2 **Literature review**
State-of-the-art of intelligent building envelopes in the context of intelligent technical systems

Research focus and knowledge gap

3 **Literature review**
Superposition matrix for the assessment of performance-relevant adaptive façade functions

Practical result

Superposition matrix

Assessment tool for automated adaptive façades

4 **Multiple case study analysis**
Automated adaptive façade functions in practice - Case studies on office buildings

Priority list of extensively automated façade functions

5 **Experiment**
Prototype of a cyber-physical façade system

Practical result

Prototype

Example architecture for a Cyber-physical façade system

6 **Conclusion**

7 **Final remarks**

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7 Final Remarks

The literature review in Chapter 2 found that the understanding of the term intelligence evolved over the years of its use. It is therefore expected that the understanding of a thinking system as it is formulated in this thesis and the associated aspects will also change in the course of emerging technologies and upcoming requirements in the future.

The project emphasizes the feasibility of façades as cyber-physical systems. Linked to such an implementation is the employment of high-tech components such as required sensors, actuators and embedded controls as well as communication devices as demonstrated in Chapter 5. The project aimed to exploit new optimization potentials in the performance of adaptive façades that lie in a possible coordination between automated façade functions. This is not a question of prefixing a new dogma for the design of façades, but rather of extending the scope of conceptual and technical possibilities. The availability of new opportunities provided by a cyber-physical implementation of façades does not contradict the exploitation of passive low-tech strategies. The actual application and design of automation concepts depends on a specific project's requirements and must be decided on a project-by-project basis. Against this background, the designer bears a great responsibility in the sensible and moderate application of respective technologies. The consideration of a cyber-physical implementation seems particularly reasonable if the employment of automation technologies is at all considered in a façade project.

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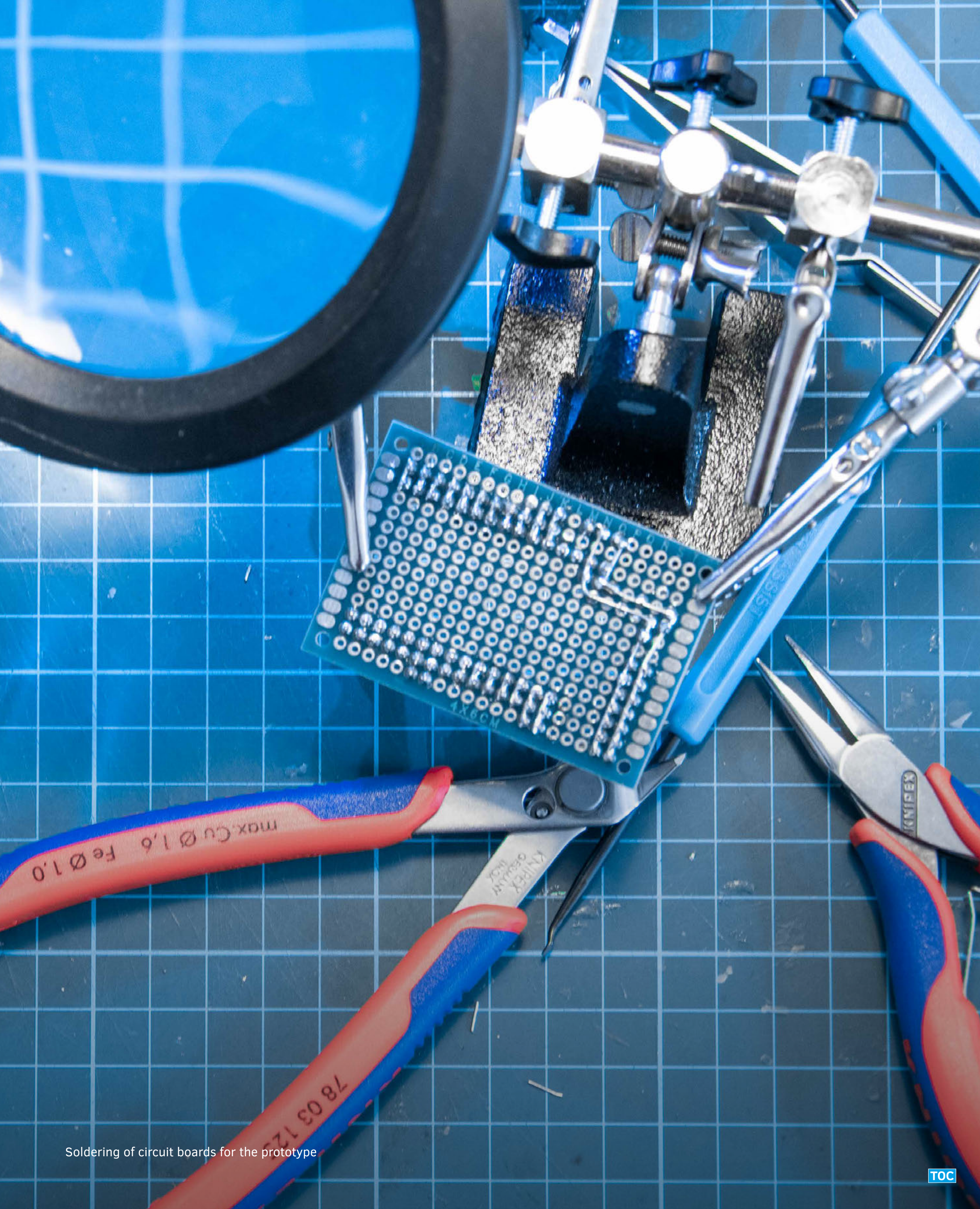

Soldering of circuit boards for the prototype

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APPENDIX A

Compilation of search terms

Table App.A.1 logs the literature search in the first state of the investigation. Based on the term combination intelligent façade and intelligent system, further search terms are identified which are used for further search iterations.

TABLE APP.A.1 Literature search protocol

INTELLIGENT façade

	INTELLIGENT **AND façade**		
Science Direct	261		
Web of science	62		
IEEExplore	48		
	Property	**Application**	**Specification**
	intelligent	façade	review
	smart	building envelope	state-of-the-art
		building skin	
		building shell	

	INTELLIGENT **AND façade** **AND review** **OR state-of-the-art**	**INTELLIGENT** **OR smart** **AND façade** **OR envelope** **OR skin OR shell**	**INTELLIGENT** **OR smart** **AND façade** **OR envelope** **OR skin** **OR shell** **AND review** **OR state-of-the-art**
Science Direct	124	804	323
Web of science	2	1268	57
IEEExplore	1	6995	11
Sum			**391**
	Property	**Application**	**Specification**
	intelligent	façade	review
	smart	building envelope	state-of-the-art
	active	building skin	concept
	responsive	building shell	principles
	high performance	curtain wall	definition
	auto reactive	double façade	
	climate adaptive	CABS	
	adaptive		
	kinetic		
	dynamic		
	advanced		

INTELLIGENT system

	INTELLIGENT AND system
Science Direct	9371
Web of science	47462
IEEExplore	170573

	Property	Application	Specification
	intelligent	system	review
	smart	technical system	state-of-the-art

	INTELLIGENT AND system AND review OR state-of-the-art	INTELLIGENT AND technical system	INTELLIGENT AND technical system AND review OR state-of-the-art
Science Direct	4972	4326	150
Web of science	2953	1870	148
IEEExplore	2168	4929	185
Sum			**483**

	Property	Application	Specification
	intelligent	system	review
	smart	technical system	state-of-the-art
	cyber-physical	cybernetics	concept
	embedded	technical cybernetics	principles
	cognitive	Internet of things (IOT)	definition
	adaptive	Industry 4.0	
	self-adaptive	‘Things that think’	
	cybernetic	Systems of Systems	
	mechatronic	Internet of everything	
	self-optimising		
	adaptronic		
	expert		

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APPENDIX B

Superposition matrix

For the cyber-physical implementation of façades, the superposition matrix in Table App.B.1 compares relevant functions with criteria for evaluating their automation and adaptivity. It serves as an organizational basis for the development of the interview guide and the systematic investigation of prerequisites in building practice in Chapter 4.

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TABLE APP.B.1 Superposition matrix

		General			Behaviour			Automation		
		Technology	Flexible	Adaptive	Operation	Response time	Degree of adaptivity	Input system	Processing system	Output system
	Sun									
1	Solar shading									
2	Light deflection									
3	Glare protection									
4	Control daylight radiation									
	Temperature									
5	Thermal insulation									
	Air									
6	Ventilation									
	User									
7	Control visual contact									
	Acoustic									
8	Sound insulation									
	Energy									
9	Generate energy									
10	Store energy									
	Supply									
11	Heating and cooling									
12	De- / humidification									
13	Electricity									
14	Artificial light									
15	Communication									

APPENDIX C

Interview guide

The interview guide was designed for carrying out expert interviews in the case studies as documented in Chapter 4. All formulated questions are derived from the findings of the superposition matrix developed in Chapter 3. The guide is divided into two main sections. The first part consists of four questions in which general information about the use of automation in the overall project is collected (Table App.C.1).

TABLE APP.C.1 Interview guide part 1

General use of automation	1	Is building automation basically used within the building / façade project?	Yes	No	NA	Closed
Platform	2	On which automation platform was it solved (if several - which ones?)	LON / BacNet / (...)			Open
Control concept	3	Is the control concept based on centralized or decentralized control?	Central	Decentral	NA	Closed
Networking	4	Does a coordination between different automated façade components / functions exist?	Yes	No	NA	Closed

The second section refers to individual façade functions, which are examined in terms of their automated adaptability. This part is hierarchically structured and, initially, only the principal consideration of a function in the façade construction is queried (Table App.C.2).

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TABLE APP.C.2 Interview guide part 2

	Sun					
1	Solar shading	Is the façade function Solar shading fulfilled in the façade construction?	*Yes*	*No*	*NA*	*Closed*
2	Light deflection	Is the façade function Light deflection fulfilled in the façade construction?	*Yes*	*No*	*NA*	*Closed*
3	Glare protection	Is the façade function Glare protection fulfilled in the façade construction?	*Yes*	*No*	*NA*	*Closed*
4	Control daylight radiation	Is the façade function Control daylight radiation fulfilled in the façade construction?	*Yes*	*No*	*NA*	*Closed*
	Temperature					
5	Thermal insulation	Is the façade function Thermal insulation fulfilled in the façade construction?	Yes	No	NA	Closed
	Air					
6	Ventilation	Is the façade function Ventilation fulfilled in the façade construction?	Yes	No	NA	Closed
	User					
7	Control visual contact	Is the façade function Control visual contact fulfilled in the façade construction?	Yes	No	NA	Closed
	Acoustic					
8	Sound insulation	Is the façade function Sound insulation fulfilled in the façade construction?	Yes	No	NA	Closed
	Energy					
9	Generate energy	Is the façade function Generate energy fulfilled in the façade construction?	Yes	No	NA	Closed
10	Store energy	Is the façade function Store energy fulfilled in the façade construction?	Yes	No	NA	Closed
	Supply					
11	Heating and cooling	Is the façade function Heating and cooling fulfilled in the façade construction?	Yes	No	NA	Closed
12	De- / humidification	Is the façade function De- / humidification fulfilled in the façade construction?	Yes	No	NA	Closed
13	Electricity	Is the façade function Electricity fulfilled in the façade construction?	Yes	No	NA	Closed
14	Artificial light	Is the façade function Artificial light fulfilled in the façade construction?	Yes	No	NA	Closed
15	Communication	Is the façade function Communication fulfilled in the façade construction?	Yes	No	NA	Closed

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Detailed questions are assigned to each section of an examined façade function, which only occur when the function has been identified as fulfilled. Since the detailed questions are identical for all functions, the following table shows an example of the composition in the case of sun shading. The detailed questions are also hierarchically structured, so that questions about the actual implementation of an automated adaptivity only arise if it exists at all (Table App.C.3).

TABLE APP.C.3 Interview guide Detailed questions

1	Solar shading	1	**Is the façade function Solar shading fulfilled in the façade construction?**				
		2	If yes	Which component or construction element fulfills this façade function?			
		3		Can its configuration be changed within the buildings use phase? (Is it flexible? Open/closed)			
		4		Does the component or construction element enable on-off or gradual states?			
		5		If yes	Is the component or construction element able to adapt itself or is a user impulse required?		
		6			Are sensors connected to the function of the component?		
		7			Does the component have actuators?		
		8			Does the component have an embedded control?		
		9			If self	In what temporal intervals do adjustments take place?	
		10			Alternative	Is the adjustment carried out by a smart material? (intrinsic)	

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	Yes	No	NA	Closed	
	Window / Lamellas /			Open	Technology
	Yes	No	NA	Closed	Flexible
	On-Off	Gradual	NA	Closed	Degree of adaptability
	Self	User	NA	Closed	Adaptive
	Yes	No	NA	Closed	Input system
	Yes	No	NA	Closed	Output system
	Yes	No	NA	Closed	Processing system
	Seconds / Hours / (...)			Semi - open	Response time
	Yes	No	NA	Closed	Operation

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APPENDIX D

Development process of the Prototype

The development process of the prototype in the fourth partial examination in Chapter 5 is documented in the composition of the following images. The figures show key moments from the conception to the fabrication of the frame modules to the integration of kinetic and electronic components.

The prototype was designed by modelling a three-dimensional model in Rhinoceros 3D according to FIG. APP.D.1 and FIG. APP.D.2. It serves as a basis for the digital fabrication of the frames as well as for the use in the realization of a digital twin.

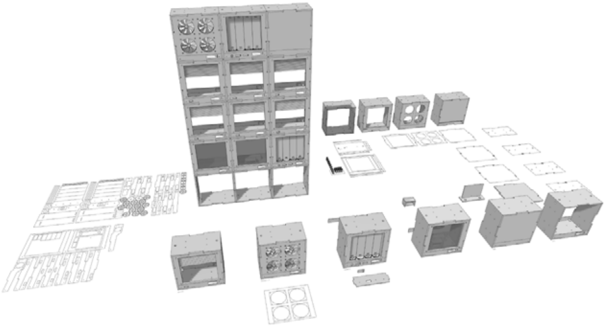

FIG. APP.D.1 3D model of the prototype in Rhinoceros as basis for the digital fabrication and implementation of a digital twin

FIG. APP.D.2 Example module of natural ventilation as 3D model

The segments of the frame modules are manufactured using a CNC milling machine and then glued together as shown in FIG. APP.D.3. Covers are mounted on one side of the frames. The closed side represents the exterior orientation and the front of the prototype. The back side stands for the inside of the façade and remains open for access to the installed technology. As visible by the cut-outs for housing fans in FIG. APP.D.4, the covers are tailored to the components of the respective façade function.

FIG. APP.D.3 Fabrication of the module frames

FIG. APP.D.4 Ready glued single modules

The modules are equipped with additional components according to a façade function represented. Before assembly, the functioning of the automation is tested. FIG. APP.D.5 shows the test run of the components representing the façade function mechanical ventilation. As shown in FIG. APP.D.6, the components are then installed in the frames.

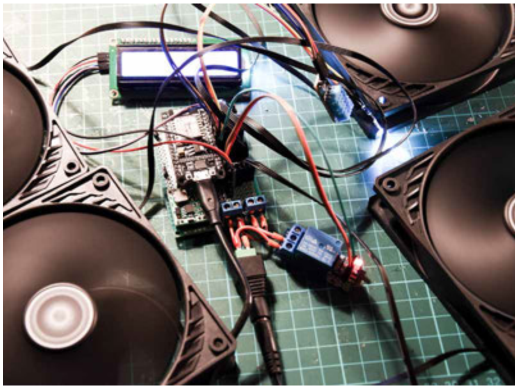

FIG. APP.D.5 Operational test of the fans for mechanical ventilation

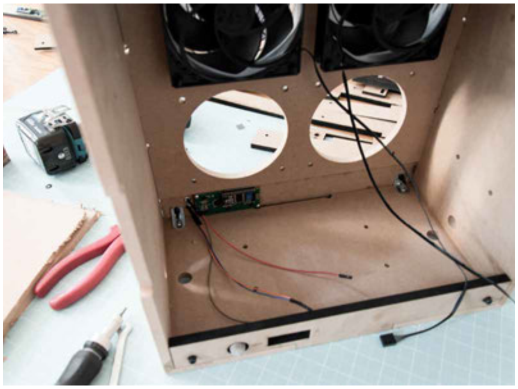

FIG. APP.D.6 Installation of the fans into the function module

FIG. APP.D.7 – FIG. APP.D.10 show the technical implementation of the other façade functions considered. This includes a gear system manufactured on the laser cutter, which is equipped with a servo motor and moves the ventilation flaps in the natural ventilation. FIG. APP.D.8 shows the integration of servo motors into the Venetian blinds used as a finished product. The raising and lowering of the lamellas is realized with a stepper motor assembly shown in FIG. APP.D.9. FIG. APP.D.10 depicts the installation of the LED strips, which are installed in the frame cover of the heating and cooling function.

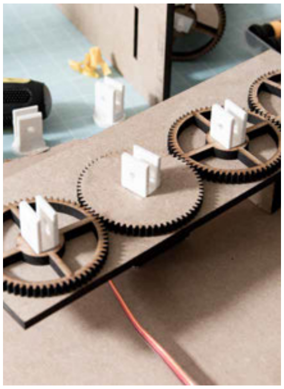

FIG. APP.D.7 Gear system for operating the ventilation flaps

FIG. APP.D.8 Integration of a servo motor in the venetian blinds of the sun protection

FIG. APP.D.9 Assembly of a stepper motor for raising and lowering the blinds

FIG. APP.D.10 Installation of LED strips to visualize the heating and cooling function

FIG. APP.D.11 - FIG. APP.D.13 demonstrate the integration of sensors, displays and LEDs into the separate control panels. The panels are screwed to the module frame using mounting brackets and can be removed or modified during the development process as well as in later maintenance of the prototype.

FIG. APP.D.11 Assembly of the control panels

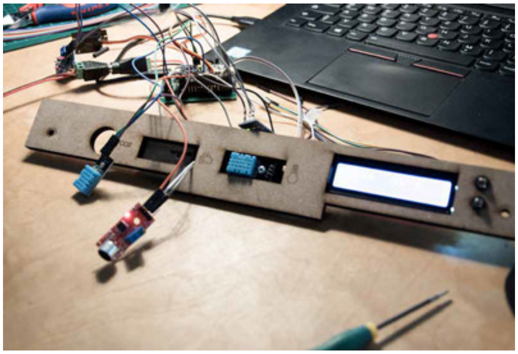

FIG. APP.D.12 Integration of sensors, displays and LEDs into the control panels

FIG. APP.D.13 Installation of the control panels into the modules

The micro-controllers integrated in the modules are reversibly installed on circuit boards. The boards are pre-soldered and equipped with sockets and plugs for the circuit. The connection to the power supply is installed as a terminal on the board. The circuit boards are mounted in the frame using screws and spacers. Jumper wires establish the connection to the sensors and actuators. The preparation of the circuit boards is shown in FIG. APP.D.14 - FIG. APP.D.16.

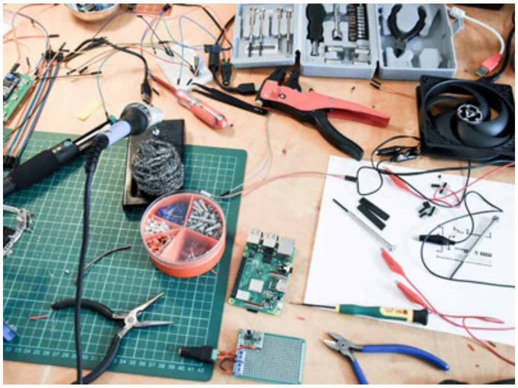

FIG. APP.D.14 Circuit board assembly

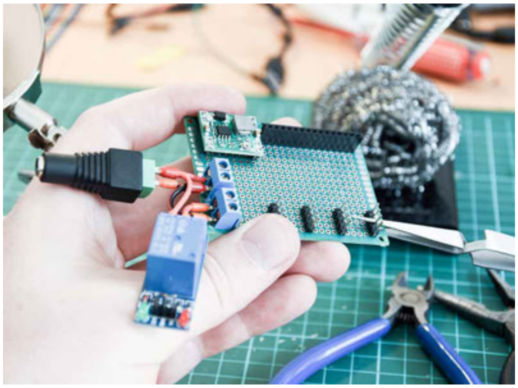

FIG. APP.D.15 Soldering the connectors

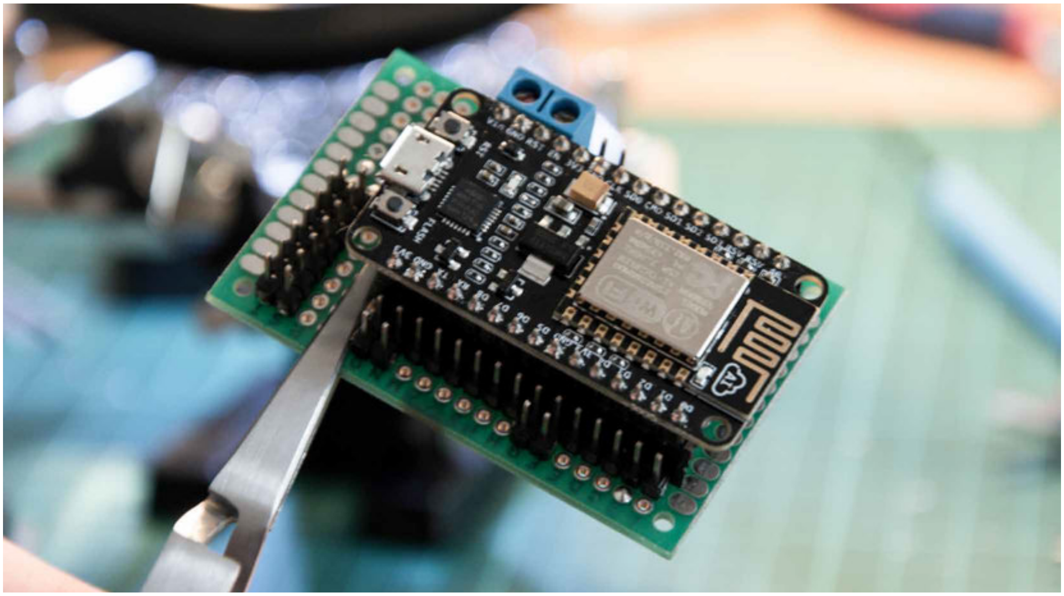

FIG. APP.D.16 Attached Node-MCU controller

One frame is equipped with a router and a Raspberry 3b+ as server of the system. Both components are supplied with power via a 12Volt adapter. A step-down module is introduced since the Raspberry Pi is in contrast to the router only designed for a voltage of 5Volt. To prevent overheating, a cooling fan is connected to the Raspberry Pi. FIG. APP.D.17 and FIG. APP.D.18 show the prepared connection and assembly of the components.

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FIG. APP.D.17 Installation of the router and server

FIG. APP.D.18 Router and server built into the technical support module

The back of the prototype gives an insight into the installed technology. FIG. APP.D.19 shows the almost finished prototype in a first test run. Clearly recognizable are the microcontrollers, which indicate the active operating state and the connection to the network via their blue illumination. FIG. APP.D.20 shows a detailed section of the technology integrated into the solar shading function with finished wiring of all sensors and actuators.

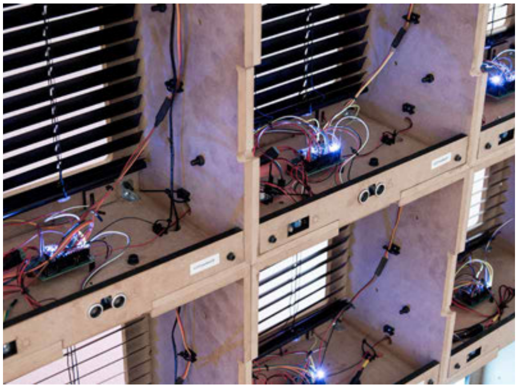


FIG. APP.D.19 Backside of the prototype in operational testing

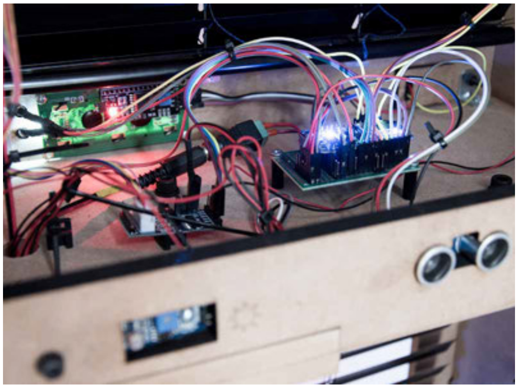


FIG. APP.D.20 Close-up of a fully implemented function

APPENDIX E

Example Code*

The appended code was programmed in the development of the prototype documented in Chapter 5. Installed on a micro-controller It regulates the façade function mechanical ventilation (mVent01). The code was developed by the use of platformIO (https://platformio.org/) and the Arduino integrated development environment (IDE) (https://www.arduino.cc/). It stands as an example for the development of four other programs controlling the solar shading, heating and cooling and natural ventilation. Like the additional code for the related digital twin, and the 3D model of the prototype, they can all be obtained from a Mendeley data set.

---

* The sample code was previously published as part of the following data set: Böke, J., Hemmerling, M., Knaack, U. (2020). *Data for: Prototype of a cyber-physical façade system.* Mendeley Data, v1. doi:10.17632/jtbn3dbxrr.1

```
// mVent
/*
Program to control the facade function “mechanical
ventilation / mVENT” written for NodeMcu V2 Amica /
ESP8266-12E Board
/ Profile NodeMcu-1.0 12E Arduino envrionment - C++
MQTT Topics
ConstructionLogic: type/clientID/specification
ConstructionExample: sensor/mVent01/temperatureInside
MQTT Wildcards
Single level (+) = sensor/+/mVent01
Multi level (#) = sensor/#
*/
// Integrate libraries
#include <Adafruit_Sensor.h> // Sensorlibrary needed for
DHT
#include <Arduino.h> // Arduino language
#include <DHT.h> // DHT temperature / humidity sensor
library
#include <ESP8266WiFi.h> // Esp8266 library
#include <LiquidCrystal_I2C.h> // Library for LCD display
#include <PubSubClient.h> // Library for the mqtt protocol
#include <Wire.h> // I2C communication
// Define Pins
const int pinLedTest = 16; // TestLED for MQTT connection
testing
const int pinLedRx = 13; // LED for receiving Data at D7
const int pinLedTx = 15; // LED for transmitting Data at D8
const int pinSda = 5; // LCD Pin D1
const int pinScl = 4; // LCD Pin D2
const int pinDht11 = 0; // DHT22 Pin D3
const int pinMqSensor = A0; // Co2 sensor at analog ADC
pin
const int pinFanSwitch = 12; // fans on/off Pin D6
const int pinFanControlSpeed = 14; // control fan speed D5
// Define Sensor Type DHT11 or DHT22
#define DHTTYPE DHT11
DHT dht(pinDht11, DHTTYPE);
// Initialize Objects
LiquidCrystal_I2C lcd(0x27, 16, 2);
// WifiClient
WiFiClient espClient;
PubSubClient client(espClient);
#define mqttPubQos 1 // qos of publish (see README)
#define mqttSubQos 1 // qos of subscribe
// Public variables
const int sensorHistory = 2;
int humidityInside[sensorHistory]; // Declare Array for
humidity
int temperatureInside[sensorHistory]; // Declare Array for
temperature
float co2Inside[sensorHistory]; // Declare Array for co2
float tempTarget = 22; // Define desired temperature
float humidTarget = 34; // Define desired humidity
float co2Target = 330; // Define desired CO2
```

```
int pwmSpeed; // variable for fanSpeed
int pwmTranslate;
float previousPwmSpeed; // variable for change detection
// Variables for network functionalities
long lastMsg = 0;
char msg[50];
long value = 0;
long lastReconnectAttempt = 0;
// Variables for Sensor value comparison
bool temperatureChange = false;
bool humidityChange = false;
bool co2Change = false;
bool fanAutoMode = true;
bool fanStatusOn = false;
bool previousfanStatusOn = false;
bool blinkRxNow = false;
bool blinkTxNow = false;
// Timer variables
const long generalTimerInterval = 2000;
const long sensorTimerInterval = 3000; // Interval to
update Values
unsigned long generalTimerCurrentMillis; // variable to
store current time
unsigned long generalTimerpreviousMillis = 0; // Variable
to store previous time
unsigned long startLedTime = 0;
unsigned long sensorTimerCurrentMillis;
unsigned long sensorTimerpreviousMillis = 0;
// MQTT topics
// string operations & translation to const char* (needed
for MQTT)
std::string functionName = “mVent01”; // change name
once
// Network variables
const char *clientID = functionName.c_str();
const char *ssid = “PrototypeNetwork”; // WLAN Network
SSID
const char *password = “Password”;              // WLAN
Password
const char *mqtt_server = “192.168.1.13”; // ServerIP
const int mqtt_port = 1883; // standard MQTT port 1883
// setup wifi connection and connect
void setup_wifi() {
delay(10);
// Connecting to a WiFi network
Serial.println();
Serial.print(“Connecting to “);
Serial.println(ssid);
WiFi.begin(ssid, password);
// Draw Dots while waiting
while (WiFi.status() != WL_CONNECTED) {
delay(500);
Serial.print(“.”);
}
// Message when connection is established
```

```
randomSeed(micros());
Serial.println(“”);
Serial.println(“WiFi connected”);
Serial.println(“IP address: “);
Serial.println(WiFi.localIP());
}
// Callback function
void callback(char *topic, byte *payload, int length) {
Serial.print(“Message arrived [“);
Serial.print(topic);
Serial.print(“] “);
for (int i = 0; i < length; i++) {
Serial.print((char)payload[i]);
}
Serial.println();
// Set StartTime for ledRx when a message arrives to
activate blink Function
startLedTime = millis();
blinkRxNow = true;
// handle topic: down/actuator/fanControl/mVent01
if (strcmp(topic, (“actuator/” + functionName + “/
fanControl”).c_str()) == 0) {
if ((char)payload[0] == ’0’) {
digitalWrite(pinFanSwitch, LOW);
fanStatusOn = false;
}
if ((char)payload[0] == ’1’) {
digitalWrite(pinFanSwitch, HIGH);
pwmSpeed = 20;
fanStatusOn = true;
} else {
}
}
if (strcmp(topic, (“actuator/” + functionName + “/
autoMode”).c_str()) == 0) {
if ((char)payload[0] == ’1’) {
fanAutoMode = true;
}
if ((char)payload[0] == ’0’) {
fanAutoMode = false;
} else {
}
}
// handle topic: down/actuator/fanSpeed/mVent01
if (strcmp(topic, (“actuator/” + functionName + “/
fanControlSpeed”).c_str()) == 0) {
payload[length] = ’\0’; // Make payload a string / NULL to
terminate it.
pwmSpeed = atoi((char *)payload);
pwmTranslate = int(map(pwmSpeed, 0, 100, 20, 1023));
analogWrite(pinFanControlSpeed, pwmTranslate);
}
// handle topic: down/target/temptarget
if (strcmp(topic, “target/tempTarget”) == 0) {
payload[length] = ’\0’; // Make payload a string / NULL to
terminate it.
tempTarget = atoi((char *)payload); // Transform char to
integer
}
if (strcmp(topic, (“actuator/” + functionName + “/
ledControl”).c_str()) == 0) {
// Switch on the LED if an 1 was received as first character
if ((char)payload[0] == ’1’) {
digitalWrite(pinLedTest, LOW);
}
if ((char)payload[0] == ’0’) {
digitalWrite(pinLedTest, HIGH);
}
}
}
// non-Blocking reconnection
boolean reconnect() {
if (client.connect(/*NAME*/ clientID)) {
// Once connected, publish an announcement...
Serial.println(“connected”);
client.publish((“status/” + functionName).c_str(),
(functionName + “: active”).c_str(), mqttPubQos);
// Subscribe to topics
client.subscribe((“actuator/” + functionName + “/+”).c_
str(), mqttSubQos);
client.subscribe(“target/tempTarget”, mqttSubQos);
}
return client.connected();
}
// Read data from the temperature/humidity sensor
void dht11Sense() {
// shift previous value to second position in array
for (int i = 0; i < sensorHistory - 1; i++) {
temperatureInside[i] = temperatureInside[i + 1];
humidityInside[i] = humidityInside[i + 1];
}
// store current value to first position in array
temperatureInside[sensorHistory - 1] = dht.
readTemperature();
humidityInside[sensorHistory - 1] = dht.readHumidity();
}
// Read data from the Co2 sensor
void mqSense() {
// shift previous value to second position in array
for (int i = 0; i < sensorHistory - 1; i++) {
co2Inside[i] = co2Inside[i + 1];
}
// store current value to first position in array
co2Inside[sensorHistory - 1] = analogRead(pinMqSensor);
}
// sensor data comparison between current and previous
void detectSensorChange() {
// stable values - just compare last 2 values for any change
if (temperatureInside[1] != temperatureInside[0]) {
temperatureChange = true;
```

```
} else {
temperatureChange = false;
}
if (humidityInside[1] != humidityInside[0]) {
humidityChange = true;
} else {
humidityChange = false;
}
// unstable values - just detect major changes between
current and
// 10th previous values / variable stores x values
int co2Difference = std::abs(co2Inside[1] - co2Inside[0]);
if (co2Difference >= 20) {
co2Change = true;
} else {
co2Change = false;
}
}
// Function LCD setup, All static elememnts on LCD-Display
void setupLcd() {
lcd.clear();
lcd.home();
lcd.print(“Temp”);
lcd.setCursor(6, 0);
lcd.print(“Humid”);
lcd.setCursor(13, 0);
lcd.print(“CO2”);
}
// Function dynamic Values on LCD Display, in loop
void valuesLCD() {
if (temperatureInside[1] >= -10 && temperatureInside[1]
<= 50) {
lcd.setCursor(0, 1);
lcd.print(String(temperatureInside[1]));
lcd.setCursor(2, 1);
lcd.print(“C”);
}
if (humidityInside[1] >= 10 && humidityInside[1] <= 60) {
lcd.setCursor(6, 1);
lcd.print(String(humidityInside[1]));
lcd.setCursor(8, 1);
lcd.print(“%”);
}
lcd.setCursor(13, 1);
lcd.print(String(co2Inside[1], 0));
}
// Control logic for the fans
void fanControl() {
// Switch relais when temp is above tempTarget
if (temperatureInside[1] >= -10 && temperatureInside[1]
<= 50) {
if (temperatureInside[1] >= tempTarget) {
// turn fan and signal-led on
digitalWrite(pinFanSwitch, HIGH);
fanStatusOn = true;
// control PWM fanSpeed
float mRange = tempTarget + 5;
pwmSpeed = min(int(map(temperatureInside[1],
tempTarget, mRange, 0, 100)), 100);
pwmTranslate = int(map(pwmSpeed, 0, 100, 0, 1023));
analogWrite(pinFanControlSpeed, pwmTranslate);
} else {
// turn fan and signal-led off
fanStatusOn = false;
digitalWrite(pinFanSwitch, LOW);
}
}
}
void blink(int led) {
digitalWrite(led, HIGH);
if (millis() - startLedTime >= 100) {
digitalWrite(led, LOW);
if (led == pinLedRx) {
blinkRxNow = false;
}
if (led == pinLedTx) {
blinkTxNow = false;
}
startLedTime = 0;
}
}
void mqttPublish() {
// publish status
client.publish((“status/” + functionName + “/
connection”).c_str(), “1”);
// MQTT publish sensor values whenever they change
if (temperatureChange == true) {
sprintf(msg, “%d\n”, temperatureInside[1]);
if (temperatureInside[1] >= -10 && temperatureInside[1]
<= 50) {
client.publish((“sensor/” + functionName + “/
temperatureInside”).c_str(), msg, mqttPubQos);
}
temperatureChange = false;
}
if (humidityChange == true) {
if (humidityInside[1] >= 10 && humidityInside[1] <= 60) {
sprintf(msg, “%d\n”, humidityInside[1]);
client.publish((“sensor/” + functionName + “/
humidityInside”).c_str(), msg, mqttPubQos);
humidityChange = false;
}
}
if (co2Change == true) {
sprintf(msg, “%.2f”, co2Inside[1]);
client.publish((“sensor/” + functionName + “/
co2Inside”).c_str(), msg, mqttPubQos);
}
if (previousfanStatusOn != fanStatusOn) {
previousfanStatusOn = fanStatusOn;
```

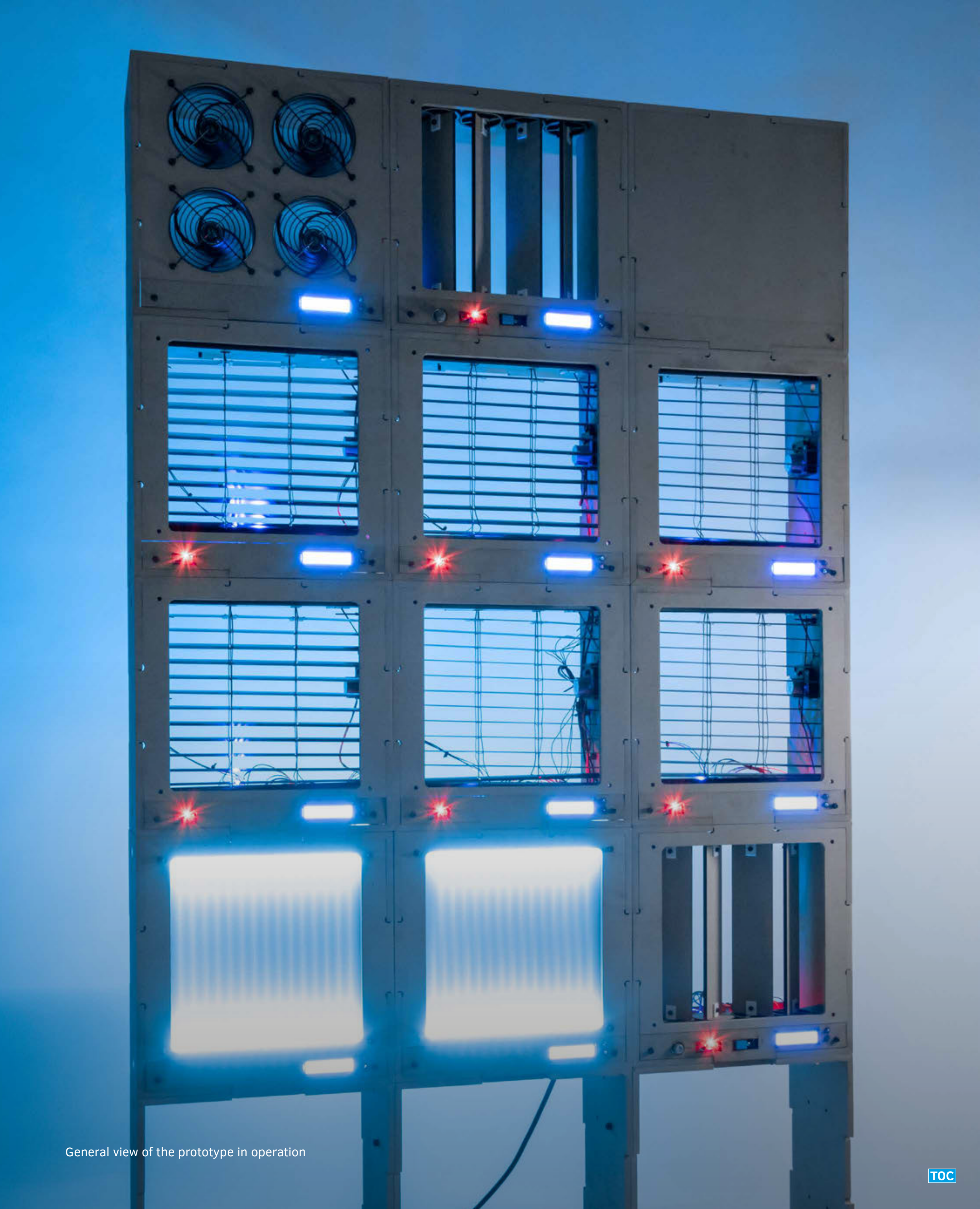
```
// // MQTT publish actuator status
if (fanStatusOn == true) {
client.publish((“actuator/” + functionName + “/
fanControl”).c_str(), “1”, mqttPubQos);
}
if (fanStatusOn == false) {
client.publish((“actuator/” + functionName + “/
fanControl”).c_str(), “0”, mqttPubQos);
}
startLedTime = millis();
blinkTxNow = true;
}
if (fanStatusOn == true && pwmSpeed !=
previousPwmSpeed) {
previousPwmSpeed = pwmSpeed;
sprintf(msg, “%d\n”, pwmSpeed);
client.publish((“actuator/” + functionName + “/
fanControlSpeed”).c_str(), msg, mqttPubQos);
startLedTime = millis();
blinkTxNow = true;
}
}
// Setup
void setup() {
// begin
Serial.begin(115200);
dht.begin();
// Connect Wifi
setup_wifi();
client.setServer(mqtt_server, mqtt_port);
client.setCallback(callback);
lastReconnectAttempt = 0;
// adjust frequency for CPU-Fans
analogWriteFreq(25000);
// Pin modes
pinMode(pinLedTest, OUTPUT);
pinMode(pinLedRx, OUTPUT);
pinMode(pinLedTx, OUTPUT);
pinMode(pinFanSwitch, OUTPUT);
pinMode(pinFanControlSpeed, OUTPUT);
pinMode(pinMqSensor, INPUT);
// Setup LCD Display and run startup Testsequence once
Wire.begin(4, 5);
lcd.begin();
// run setup static Output for LCD-Display
setupLcd();
// set initial sensor Array values to zero
for (int i = 0; i < sensorHistory; i++) {
temperatureInside[i] = 0;
humidityInside[i] = 0;
co2Inside[i] = 0;
}
}
// Loop
void loop() {
```

```
// non-Blocking reconnection to server
if (!client.connected()) {
long now = millis();
if (now - lastReconnectAttempt > 5000) {
lastReconnectAttempt = now;
Serial.println(“connection failed- next try in 5sec”);
// Attempt to reconnect
if (reconnect()) {
lastReconnectAttempt = 0;
}
}
} else {
// Client connected
client.loop();
}
// when triggered by incoming and outgoing messages run
the blink function
// for Rx or Tx
if (blinkRxNow == true) {
blink(pinLedRx);
}
if (blinkTxNow == true) {
blink(pinLedTx);
}
// timed actions depending on defined variable
sensorTimerInterval
sensorTimerCurrentMillis = millis();
if (sensorTimerCurrentMillis - sensorTimerpreviousMillis >=
sensorTimerInterval) {
sensorTimerpreviousMillis = sensorTimerCurrentMillis;
// Input - continuously sense in defined intervals
dht11Sense();
mqSense();
// test if sensor data has changed
detectSensorChange();
}
// timed actions depending on defined variable
generalTimerInterval
generalTimerCurrentMillis = millis();
if (generalTimerCurrentMillis - generalTimerpreviousMillis
>= generalTimerInterval) {
generalTimerpreviousMillis = generalTimerCurrentMillis;
mqttPublish();
// Output - actions based on processed information
valuesLCD();
// run fans based on the feedbackloop
if (fanAutoMode == true) {
fanControl();
} else {
}
}
}
```

```
MQTTClient digitalTwin;
Listener input;
Frame skeleton;
DynObjects movingParts;
Hud information;

// Define global variables
int backgroundCol = 255;
int lightIntensity = 220;
int payloadInteger;
String payloadString;
String payloadStringTrimmed;
int nVent01FlapsControl;

void setup() {
  // Setup camera
  cam = new PeasyCam(this, 1045 / 2, -1000, 0, 1800);
  cam.setYawRotationMode();     // Limit rotation to y-axis
  cam.setMinimumDistance(800);  // Keep this minimum distance to the geometry
  cam.setMaximumDistance(2800); // Keep this maximum distance to the geometry

  // Setup viewport in 3DMode - Alternatively in fullscreen
  // size(1024, 768, P3D); //Set viewport to Resolution in 3DMode
  fullScreen(P3D);           // Set viewport to fullscreen in 3DMode
  background(backgroundCol); // Fill Backgroundcolour
  frameRate(60);

  // Setup Client
  digitalTwin = new MQTTClient(this);
  digitalTwin.connect("tcp://192.168.1.13:1883", "digitalTwin");

  // Create Objects
  input = new Listener();  // Read values by serial communication from Arduino
  skeleton = new Frame();  // Frame geometry + floor
  information = new Hud(); // 2D Textelements
  movingParts =
      new DynObjects(); // Dynamic components sorted in one class
}

void draw() {
  // Loop setup scene
  lights(); // Illumination on
  pointLight(lightIntensity, lightIntensity, lightIntensity, width / 2, 3000,
             -400);          // Add Omni-Light
  background(backgroundCol); // Clear Background to Backgroundcolour

  input.assignData();
  skeleton.display();
  movingParts.display();
  information.display();
}

void clientConnected() {
  println("client connected");
  digitalTwin.subscribe("sensor/#");
  digitalTwin.subscribe("actuator/#");
}
```

Appearance of code in the Atom editor

TOC



General view of the prototype in operation

References

Addington, M. (2009). Contingent Behaviours. *Architectural Design, 79*, 12-17. doi:10.1002/ad.882

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

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

Al horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment, 5*, 1-11. doi:10.1016/j.ijsbe.2016.03.006

Alexander, C., Ishikawa, S., & Silverstein, M. (1977). *A pattern language : towns, buildings, construction*. New York: Oxford University Press.

Alexander, C., Koolhaas, R., & Obrist, H. U. (2008). Von fließender Systematik und generativen Prozessen [Of fluid systematics and generative processes]. *Arch+, 189,* 20-25.

Alhammadi, A., Alzaabi, A., Almarzooqi, B., Alneyadi, S., Alhashmi, Z., & Shatnawi, M. (2019). Survey of IoT-Based Smart Home Approaches. *2019 Advances in Science and Engineering Technology International Conferences (ASET)*, Dubai, United Arab Emirates, 2019, 1-6. doi:10.1109/ICASET.2019.8714572

Anshuman, S. (2005). Responsiveness and Social Expression, Seeking Human Embodiment in Intelligent Façades. *Smart Architecture: Integration of Digital and Building Technologies. Proceedings of the 2005 Annual Conference of the Association for Computer Aided Design In Architecture (ACADIA)*, Savannah, Georgia, 2005, 12-23. Retrieved from http://papers.cumincad.org/data/works/att/acadia05_012.content.pdf

Attia, S., Bilir, S., Safy, T., Struck, C., Loonen, R., & Goia, F. (2018). Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy and Buildings, 179*, 165-182. doi: 10.1016/j.enbuild.2018.09.017

Bähre, B. (2018). Building Information Modeling: The 'C' in BIM. In M. Hemmerling & L. Cocchiarella (Eds.), *Informed Architecture: Computational Strategies in Architectural Design* (pp. 39-52). Cham: Springer International Publishing.

Bai, S. A. (2011). Artificial intelligence technologies in business and engineering. *International Conference on Sustainable Energy and Intelligent Systems (SEISCON 2011)*, Chennai, 2011, 856-859. doi:10.1049/cp.2011.0486

Bakker, L. G., Hoes-van Oeffelen, E. C. M., Loonen, R. C. G. M., & Hensen, J. L. M. (2014). User satisfaction and interaction with automated dynamic facades: A pilot study. *Building and Environment, 78*, 44-52. doi:10.1016/j.buildenv.2014.04.007

Balance: HPP Architekten. (2013). (F. Maier-Solgk & H. H.-P. Partner Eds. Dt. Ausg. ed.). Ostfildern: Hatje Cantz.

Becker, E., Biesenbach, K., Humpert, K., & Schuler, M. (2012). *Superferenz* (E. Becker, K. Biesenbach, K. Humpert, R. Stegers, & E. Becker_Architekten Eds.). Ostfildern: Hatje Cantz.

Bitan, A. (1988). The methodology of applied climatology in planning and building. *Energy and Buildings, 11*, 1-10. doi:10.1016/0378-7788(88)90018-7

BITKOM, VDMA, ZVEI: Umsetzungsstrategie Industrie 4.0. [Implementation Strategy Industry 4.0.] (2015). Retrieved from https://www.bitkom.org/sites/default/files/file/import/150410-Umsetzungsstrategie-0.pdf

Bittencourt, L., Immich, R., Sakellariou, R., Fonseca, N., Madeira, E., Curado, M., . . . Rana, O. (2018). The Internet of Things, Fog and Cloud continuum: Integration and challenges. *Internet of Things, 3-4*, 134 - 155. doi:10.1016/j.iot.2018.09.005

Bitterman, N., & Shach-Pinsly, D. (2015). Smart home - a challenge for architects and designers. *Architectural Science Review, 58*, 266-274. doi:10.1080/00038628.2015.1034649

Blaser, W. (2004). *Post tower: Helmut Jahn, Werner Sobek, Matthias Schuler*. Basel: Birkhäuser.

Bogner, A., Littig, B., & Menz, W. (2014). *Interviews mit Experten* [Interviews with experts]. Wiesbaden: Springer VS Fachmedien Wiesbaden.

Böke, J. (2009). *SunSys.* (BA), Ostwestfalen-Lippe University of Applied Sciences, Detmold (Unpublished bachelor's thesis).

Böke, J., Knaack, U., & Hemmerling, M. (2018). State-of-the-art of intelligent building envelopes in the context of intelligent technical systems. *Intelligent Buildings International*, 1-19. doi:10.1080/17508975.2018.1447437

Böke, J., Knaack, U., & Hemmerling, M. (2019). Superposition matrix for the assessment of performance-relevant adaptive façade functions. *Journal of Facade Design and Engineering, 7*(2), 1-20. doi:10.7480/jfde.2019.2.2463

Böke, J., Knaack, U., & Hemmerling, M. (2020). Automated adaptive façade functions in practice - Case studies on office buildings. *Automation in Construction, 113*, 103113. doi:10.1016/j.autcon.2020.103113

Brensing, C. (2012). Tief aus der Erde von Hannover. Zentrale des HDI-Gerling Konzerns [Deep from the ground of Hannover. Headquarters of the HDI-Gerling Group]. *Bauwelt, 103,* 24-29.

Brettel, M. , Friederichsen, N. , Keller, M. , Rosenberg, M. (2014). How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective. *World Academy of Science, Engineering and Technology, Open Science Index 85, International Journal of Information and Communication Engineering*, 8(1), 37 - 44. doi:10.5281/zenodo.1336426

Broy, M. (2010). Cyber-Physical Systems — Wissenschaftliche Herausforderungen Bei Der Entwicklung [Cyber-Physical Systems - Scientific challenges during the development]. In M. Broy (Ed.), *Cyber-Physical Systems* (pp. 17-31). Berlin, Heidelberg: Springer Berlin Heidelberg.

Building Information Modeling: Technology Foundations and Industry Practice. (2018). (A. Borrmann, M. König, C. Koch, & J. Beetz Eds.). Cham: Springer International Publishing.

Bullivant, L. (2006). *Responsive environments : architecture, art, and design*. London New York: V & A Publications ; Distributed in North America by Harry N. Abrams.

Carl, T. (2019). Ecologies of Skin and Depth. *Deep Skin Architecture: Design Potentials of Multi-Layered Architectural Boundaries* (pp. 13-53). Wiesbaden: Springer Fachmedien Wiesbaden.

Châlons, C., & Dufft, N. (2016). Die Rolle der IT als Enabler für Digitalisierung [The role of IT as an enabler for digitalization]. In F. Abolhassan (Ed.), *Was treibt die Digitalisierung? Warum an der Cloud kein Weg vorbeiführt* (pp. 27-37). Wiesbaden: Springer Fachmedien Wiesbaden.

Clements-Croome, T. D. J. (1997). What do we mean by intelligent buildings? *Automation in Construction, 6*, 395-400. doi:10.1016/S0926-5805(97)00018-6

Compagno, A. (1999). *Intelligente Glasfassaden: Material, Anwendung, Gestaltung* [Intelligent glass façades: material, practice, design] (4th, rev. and enlarged ed ed.). Basel ; Boston: Birkhäuser-Verlag.

Complex: die Architektur von KSP Engel und Zimmermann [Complex: the architecture by KSP Engel und Zimmermann]. (2004). (I. Flagge, P. Davey, & K. E. u. Z. A. GmbH Eds.). Ostfildern-Ruit: Hatje Cantz.

Çorak, B. H., Okay, F. Y., Güzel, M., Murt, S., & Ozdemir, S. (2018). Comparative Analysis of IoT Communication Protocols. *2018 International Symposium on Networks, Computers and Communications (ISNCC)*, Rome, 2018, 1-6. doi:10.1109/ISNCC.2018.8530963

Cudzik, J., Nyka, L., & Iop. (2017). Reasons for Implementing Movement in Kinetic Architecture. *World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium - Wmcaus*, 245(4). doi: 10.1088/1757-899x/245/4/042073

Czichos, H. (2015). *Mechatronik: Grundlagen und Anwendungen technischer Systeme* [Mechatronics: Fundamentals and applications of technical systems] (3., überarb. u. erw. Aufl. 2015 ed.). Wiesbaden: Springer Fachmedien Wiesbaden GmbH.

Dahl, T. (2010). *Climate and architecture* (1st ed ed.). Milton Park, Abingdon, Oxon ; New York, N.Y: Routledge.

Datta, S., & Sarkar, S. (2018). Automation, security and surveillance for a smart city: Smart, digital city. *Proceedings of the 2017 IEEE Calcutta Conference,* CALCON 2017. doi:10.1109/CALCON.2017.8280689

Davies, M. (1981). A Wall for All Seasons. *RIBA Journal-Royal Institute of British Architects, 88*(2), 55-57.

Dawson, L. (2011, 2011). Oval Offices, Cologne - Sauerbruch Huttom. *ARCHITECTURAL RECORD, 199; Jg. 2011*, 84-87.

Del Grosso, A. E., & Basso, P. (2010). Adaptive building skin structures. *Smart Materials and Structures, 19*. doi:10.1088/0964-1726/19/12/124011

Deplazes, A. (2013). *Constructing architecture : materials, processes, structures : a handbook* (Third, extended edition. ed.). Basel: Birkhäuser.

Design Methodology for Intelligent Technical Systems. (2014). (J. Gausemeier, F. J. Rammig, & W. Schäfer Eds.). Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg.

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, (2010). Retrieved from https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32010L0031

Disch R. (1995). Heliotrope in Freiburg by Rolf Disch [Photograph]. Retrieved from http://www.rolfdisch.de/media-de/bildarchiv/#heliotrop

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

Douglas, J. (1996). Building performance and its relevance to facilities management. *Facilities, 14*, 23-32. doi:10.1108/02632779610112508

Drossel, W.-G., Kunze, H., Bucht, A., Weisheit, L., & Pagel, K. (2015). Smart3 – Smart Materials for Smart Applications. *Procedia CIRP, 36*, 211-216. doi:10.1016/j.procir.2015.01.055

Dumitrescu, R., Jürgenhake, C., & Gausemeier, J. (2012). *Intelligent Technical Systems OstWestfalenLippe*. Paper presented at the 1stJoint International Symposium on System-Integrated Intelligence 2012: New Challenges for Product and Production Engineering, Hannover. Retrieved from http://www.2012.sysint-conference.org/fileadmin/SysInt_Files/SysInt2012/Session1/Intelligent_Technical_Systems_OstWestfalenLippe_168_kui_schw_he.pdf

El-Khoury, R., Marcopoulos, C., Moukheiber, C., & Adams, D. (2012). *Make alive: protoypes for responsive architectures*. Hong Kong: Oscar Riera Ojeda Publishers.

Elkhateeb, A. M., Fikry, M. A., & Mansour, A. A. (2018). Dynamic building and its impact on sustainable development. *Alexandria Engineering Journal, 57*(4), 4145-4155. doi:10.1016/j.aej.2018.10.016

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

Fassaden: best of Detail -Facades. (2015). (C. Schittich, S. Lenzen, & I. f. I. Architektur-Dokumentation Eds. 1. Aufl ed.). München: Inst. für Internationale Architektur-Dokumentation.

Fassaden: Gebäudehüllen für das 21. Jahrhundert [Facades: Building envelopes for the 21st century]. (2010). (D. U. Hindrichs & W. Heusler Eds. 3., erw. Aufl ed.). Basel: Birkhäuser.

Favoino, F., Goia, F., Perino, M., & Serra, V. (2016). Experimental analysis of the energy performance of an ACTive, RESponsive and Solar (ACTRESS) façade module. *Solar Energy, 133*, 226-248. doi:10.1016/j.solener.2016.03.044

Favoino, F., Jin, Q., & Overend, M. (2014). Towards an Ideal Adaptive Glazed Façade for Office Buildings. *6th International Conference on Sustainability in Energy and Buildings, SEB-14, 62*, 289-298. doi:10.1016/j.egypro.2014.12.390

Fortmeyer, R. M., & Linn, C. D. (2014). *Kinetic architecture : designs for active envelopes*. Mulgrave, Victoria: Images Publishing Group.

Frazer, J. (1995). *An evolutionary architecture*. London: Architectural Association.

From machine-to-machine to the Internet of things: introduction to a new age of intelligence. (2014). (J. Höller Ed.). Amsterdam: Elsevier Academic Press.

García-Gil, D., Luengo, J., García, S., & Herrera, F. (2019). Enabling Smart Data: Noise filtering in Big Data classification. *Information Sciences, 479*, 135-152. doi:10.1016/j.ins.2018.12.002

Gausemeier, J., Anacker, H., Czaja, A. M., Wassmann, H., & Dumitrescu, R. (2013). Auf dem Weg zu intelligenten technischen Systemen [On the way to intelligent technical systems]. *In 9. Paderborner Workshop Entwurf mechatronischer Systeme*, 310, Paderborn: Verlagsschriftenreihe des Heinz Nixdorf Instituts.

Givoni, B. (1976). *Man, climate and architecture*. London: Applied Science Publishers

González, B., Holl, C., Fuhrhop, D., & Dale, M. (2010). *KfW Westarkade Frankfurt am Main: energy-efficient office building*. Berlin: Stadtwandel-Verlag.

Görz, G., & Schneeberger, J. (2003). *Handbuch der künstlichen Intelligenz* [Artificial intelligence manual]. München: De Gruyter Oldenbourg.

Granzer, W., Praus, F., & Kastner, W. (2010). Security in Building Automation Systems. *IEEE Transactions on Industrial Electronics, 57*(11), 3622-3630. doi:10.1109/TIE.2009.2036033

Gruber, P., & Gosztonyi, S. (2010). *Skin in architecture: towards bioinspired facades.* Paper presented at the DESIGN AND NATURE 2010. doi:10.2495/DN100451

Gruber, T. (2009). Ontology. In L. Liu & M. T. ÖZsu (Eds.), *Encyclopedia of Database Systems* (pp. 1963-1965). Boston, MA: Springer US.

Gudivada, V. N. (2016). Chapter 1 - Cognitive Computing: Concepts, Architectures, Systems, and Applications. In V. N. Gudivada, V. V. Raghavan, V. Govindaraju, & C. R. Rao (Eds.), *Handbook of Statistics* (Vol. 35, pp. 3-38): Elsevier. doi:10.1016/bs.host.2016.07.004

Haake, A., Scott, G. A., & Holbrook, K. A. (2001). Structure and function of the skin: overview of the epidermis and dermis. In R.K. Freinkel & D.T. Woodley (Eds.), *The biology of the skin.* 19-45. New York: Parthenon Pub. Group.

Hartkopf, V., & Loftness, V. (1999). Global relevance of total building performance. *Automation in Construction, 8* (4), 377-393. doi:10.1016/S0926-5805(98)00085-5

Hasselaar, B. (2013). *The comfort unit: developed as part of a climate adaptive skin* (Doctoral thesis). Retrieved from https://repository.tudelft.nl/islandora/object/uuid:83f692c1-38a5-4fbf-8138-d78346d046db. doi:10.4233/uuid:83f692c1-38a5-4fbf-8138-d78346d046db

Hauschild, M., & Karzel, R. (2010). *Digitale Prozesse: Planung, Gestaltung, Fertigung* [Digital processes: Planning, design, production] (1. Aufl ed.). München: Inst. für Internat. Architektur-Dokumentation.

Hausladen, G., de Saldanha, M., Liedl, P., & Sager, C. (2005). *Climate design: solutions for buildings that can do more with less technology*. Basel, Switzerland: Birkhäuser.

Hausladen, G., Liedl, P., & Saldanha, M. d. d. (2012). *Klimagerecht bauen: ein Handbuch* [Building to Suit the Climate: A Handbook]. Basel: Birkhäuser.

Hausladen, G., Saldanha, M. d., & Liedl, P. (2008). *Climateskin: concepts for building skins that can do more with less energy*. Basel; Boston: Birkhäuser.

Haykin, S., Amiri, A., & Fatemi, M. (2014). *Cognitive control in cognitive dynamic systems: A new way of thinking inspired by the brain. 2014 IEEE Symposium on Adaptive Dynamic Programming and Reinforcement Learning (ADPRL)*, Orlando, FL, 2014. 1-7. doi:10.1109/ADPRL.2014.7010623

Hemmerling, M. (2018). Informed Architecture. In M. Hemmerling & L. Cocchiarella (Eds.), *Informed Architecture: Computational Strategies in Architectural Design* (pp. 3-10). Cham: Springer International Publishing.

Hemmerling, M., & Böke, J. (2014). *SunSys - A Case Study on Geometric Complexity in Computational Design.* Paper presented at the 16th International Conference on Geometry and Graphics, Innsbruck, 2014.

Hemmerling, M., Nether, U., & Böke, J. (2018). SunSys. In M. Hemmerling & L. Cocchiarella (Eds.), *Informed Architecture* (pp. 129-138). Cham: Springer International Publishing.

Herwan, J., Kano, S., Oleg, R., Sawada, H., & Kasashima, N. (2018). Cyber-physical system architecture for machining production line. *2018 IEEE Industrial Cyber-Physical Systems (ICPS)*, St. Petersburg, 2018, 387-391. doi:10.1109/ICPHYS.2018.8387689

Herzog, T., Krippner, R., & Lang, W. (2004). *Facade construction manual.* Basel; Boston: Birkhauser-Publishers for Architecture.

Hicks, M. (2006). Milwaukee art museum by Santiago Calatrava [Photograph]. Retrieved from https://upload.wikimedia.org/wikipedia/commons/7/79/Milwaukee_Art_Museum_1_%28Mulad%29.jpg

Hoffmann, D., Folkmer, B., & Manoli, Y. (2010). Multi-parameter optimization of electrostatic micro-generators using design optimization algorithms. *Smart Materials and Structures, 19*(11). doi:10.1088/0964-1726/19/11/115016

Hu, L., Xie, N., Kuang, Z., & Zhao, K. (2012). Review of cyber-physical system architecture. *2012 IEEE 15th International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing Workshops*, Shenzhen, Guangdong, 2012. 25-30. doi:10.1109/ISORCW.2012.15

ICD University of Stuttgart (2012). HygroScope: Meteorosensitive Morphology [Photograph]. Retrieved from https://www.icd.uni-stuttgart.de/projects/hygroscope-meteorosensitive-morphology/

Inhabitat (2014). Responsive façade of the Al Bahr towers in Abu Dhabi by Aedas Architects [Photograph]. Retrieved from https://www.flickr.com/photos/inhabitat/12330988375/sizes/l/

Intelligent - definition of intelligent in English | Oxford Dictionaries. (2017). *Oxford Dictionaries | English.*

Interactive architecture: adaptive world. (2016). (M. Fox Ed. First edition ed.). New York: Princeton Architectural Press.

Jencks, C. (1997). Nonlinear Architecture. In M. Carpo (Ed.), *The Digital Turn in Architecture 1992-2012* (pp. 80-107). Hoboken, NJ, USA: John Wiley & Sons, Inc.

Joncas, R. MQTT and CoAP, IoT Protocols | The Eclipse Foundation. Retrieved November 11, 2019, from https://www.eclipse.org/community/eclipse_newsletter/2014/february/article2.php

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

Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0, Final report of the Industrie 4.0 Working Group.* Retrieved from: https://www.din.de/blob/76902/e8cac883f42bf28536e7e8165993f1fd/recommendations-for-implementing-industry-4-0-data.pdf

Karanouh, A., & Kerber, E. (2015). Innovations in dynamic architecture. *Journal Of Facade Design And Engineering*, 3(2), 185-221. doi:10.7480/jfde.2015.2.1017

Kast, F. E., & Rosenzweig, J. E. (1972). General Systems Theory: Applications for Organization and Management. *The Academy of Management Journal, 15*(4), 447-465. doi:10.2307/255141

Kastner, W., Neugschwandtner, G., Soucek, S., & Newman, H. M. (2005). Communication systems for building automation and control. *Proceedings of the IEEE, 93*(6), 1178-1203. doi:10.1109/Jproc.2005.849726

Kawaguchi, R., & Bandai, M. (2019). A Distributed MQTT Broker System for Location-based IoT Applications. *2019 IEEE International Conference on Consumer Electronics (ICCE)*, Las Vegas, NV, USA, 2019, 1-4. doi:10.1109/ICCE.2019.8662069

Kirste, M., & Schürholz, M. (2019). Einleitung: Entwicklungswege zur KI [Introduction: Development paths to AI]. In V. Wittpahl (Ed.), *Künstliche Intelligenz: Technologie | Anwendung | Gesellschaft* (pp. 21-35). Vieweg, Berlin, Heidelberg: Springer.

Klein, T. (2013). *Integral Facade Construction: Towards a new product architecture for curtain walls* (Doctoral thesis). Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3Af90c1c7e-b6b3-42de-8f17-22cc23981de7

Knaack, U., Hildebrand, L., Ashour, A., Pottgiesser, U., Böke, J., & Ernst, M. (2016). *Prototyping efnMobile.* Rotterdam: Nai010 Publishers.

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2014). *Façades: principles of construction* (Second and revised edition ed.). Basel: Birkhäuser.

Kolarevic, B. (2003). *Architecture in the digital age : design and manufacturing.* New York, NY: Spon Press.

Kolarevic, B. (2015). Towards Architecture of Change. In B. Kolarevic & V. Parlac (Eds.), *Building dynamics : exploring architecture of change* (pp. 2-16). London ; New York: Routledge.

Kretzer, M., & Hovestadt, L. (2014). *Alive : advancements in adaptive architecture.* Basel: Birkäuser.

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine, 51*(11), 1016 - 1022. doi:10.1016/j.ifacol.2018.08.474

Kroner, W. M. (1997). An intelligent and responsive architecture. *Automation in Construction, 6*(5-6), 381-393. doi:10.1016/S0926-5805(97)00017-4

Kucera, A., & Pitner, T. (2016). Semantic BMS: Ontology for Analysis of Building Automation Systems Data. *Technological Innovation for Cyber-Physical Systems, 470*, 46-53. doi:10.1007/978-3-319-31165-4_5

Le Corbusier, Cohen, J.-L., & Goodman, J. (2007). *Toward an architecture.* Los Angeles, Calif.: Getty Research Institute.

LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. *Nature, 521*(7553), 436-444. doi:10.1038/nature14539

Lee, E. A. (2008). Cyber Physical Systems: Design Challenges. *11th IEEE International Symposium on Object and Component-Oriented Real-Time Distributed Computing (ISORC) 2008*, 363-369. doi:10.1109/ISORC.2008.25

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters, 3*, 18-23. doi:10.1016/j.mfglet.2014.12.001

Lee, S., Kim, H., Hong, D., & Ju, H. (2013). Correlation analysis of MQTT loss and delay according to QoS level. *The International Conference on Information Networking 2013 (ICOIN)*, Bangkok, 2013, 714-717. doi:10.1109/ICOIN.2013.6496715

Lexcellent, C. (2019). Artificial Intelligence. In C. Lexcellent (Ed.), *Artificial Intelligence versus Human Intelligence: Are Humans Going to Be Hacked?* (pp. 5-21). Cham: Springer International Publishing.

Lignarolo, L. E. M., Lelieveld, C. M. J. L., & Teuffel, P. (2011). *Shape morphing wind-responsive facade systems realized with smart materials*. Paper presented at the Adaptive Architecture: An International Conference London, UK. Retrieved from http://resolver.tudelft.nl/uuid:be165d55-9acb-4f1a-9cc1-5685d33676f1

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

Loonen, R. C. G. M., Favoino, F., Hensen, J. L. M., & Overend, M. (2017). Review of current status, requirements and opportunities for building performance simulation of adaptive facades. *Journal of Building Performance Simulation, 10(2)*, 205-223. doi:10.1080/19401493.2016.1152303

Loonen, R. C. G. M., Rico-Martinez, J. M., Favoino, F., Brzezicki, M., Menezo, C., La Ferla, G., & Aelenei, L. (2015). *Design for façade adaptability: Towards a unified and systematic characterization*. Paper presented at the 10th Conference on Advanced Building Skins, Bern, Switzerland.1284-1294. Munich: Economic Forum. Retrieved from https://pure.tue.nl/ws/portalfiles/portal/8287122/15_abs_loonen.pdf

Macias-Escriva, F. D., Haber, R., del Toro, R., & Hernandez, V. (2013). Self-adaptive systems: A survey of current approaches, research challenges and applications. *Expert Systems with Applications, 40*, 7267-7279. doi:10.1016/j.eswa.2013.07.033

Maeda, J. (2019). *How to speak machine : computational thinking for the rest of us*. New York: Portfolio.

Mathews, S. (2005). The Fun Palace: Cedric Price's experiment in architecture and technology. *Technoetic Arts, 3*(2), 73-92. doi:10.1386/tear.3.2.73/1

McCarthy, J., Minsky, M. L., Rochester, N., & Shannon, C. E. (2006). A proposal for the dartmouth summer research project on artificial intelligence, august 31, 1955. *AI magazine*, 27(4), 12-12. doi: 10.1609/aimag.v27i4.1904

Meagher, M. (2015). Designing for change: The poetic potential of responsive architecture. *Frontiers of Architectural Research, 4(2)*, 159-165. doi:10.1016/j.foar.2015.03.002

Menges, A., & Ahlquist, S. (2011). *Computational design thinking: computation design thinking*: John Wiley & Sons.

Menges, A., Reichert, S., & Krieg, O. D. (2014). Meteorosensitive Architectures. In M. Kretzer & L. Hovestadt (Eds.), *Meteorosensitive Architectures. ALIVE: Advancements in adaptive architecture* (pp. 39–42). Basel: Birkäuser.

Merz, H., Hansemann, T., & Hubner, C. (2009). Introduction to Building Automation. *Building Automation*, 1-25. doi:10.1007/978-3-540-88829-1_1

Möllering, C. (2017). *A platform for autonomous, facade integrated room control* (Doctoral thesis). Aachen: Apprimus Verlag.

Moloney, J. (2011). *Designing Kinetics for Architectural Facades: State Change. Abingdon, Oxon:* Routledge.

Monedero, J. (2000). Parametric design: a review and some experiences. *Automation in Construction, 9*(4), 369-377. doi:10.1016/S0926-5805(99)00020-5

Monostori, L. (2014). Cyber-physical Production Systems: Roots, Expectations and R&D Challenges. *Procedia CIRP, 17*, 9-13. doi:10.1016/j.procir.2014.03.115

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., . . . Ueda, K. (2016). Cyber-physical systems in manufacturing. *CIRP Annals - Manufacturing Technology, 65*(2), 621-641. doi:10.1016/j.cirp.2016.06.005

mppf - The multifunctional plug&play approach in facade technology. (2015). (T. Mach, M. Grobbauer, W. Streicher, & M. J. Müller Eds.). Graz: Verlag der Technischen Universität Graz.

MQTT Version 5.0. (15 May 2018). Retrieved from http://docs.oasis-open.org/mqtt/mqtt/v5.0/cs02/mqtt-v5.0-cs02.html. Latest version: http://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.html.

Murphy, I. (1990). Intelligent Buildings. *ARCH+, 104,* 26-31.

Negri, E., Fumagalli, L., & Macchi, M. (2017). A Review of the Roles of Digital Twin in CPS-based Production Systems. *27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy, 11*, 939-948. doi:10.1016/j.promfg.2017.07.198

Ochoa, C. E., & Capeluto, I. G. (2008). Strategic decision-making for intelligent buildings: Comparative impact of passive design strategies and active features in a hot climate. *Building and Environment, 43*, 1829-1839. doi:10.1016/j.buildenv.2007.10.018

OECD (2018), *OECD Science, Technology and Innovation Outlook 2018: Adapting to Technological and Societal Disruption*. Paris: OECD Publishing. doi:10.1787/sti_in_outlook-2018-en.

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry, 83*, 121-139. doi:10.1016/j.compind.2016.09.006

Ott P. (2007). Kiefer Technic Showroom [Photograph]. Retrieved from https://www.graz-cityofdesign.at/images_dynam/image_zoomed/paul-ott_detail02.jpg

Oxman, R. (2017). Parametric design thinking. *Design Studies, 52*, 1-3. doi:10.1016/j.destud.2017.07.001

Pask, G. (1969). The architectural relevance of cybernetics. *Architectural Design, 39*(9), 494-496.

Plotczyk, M., & Higgins, C. A. (2019). 1 - Skin biology. In E. García-Gareta (Ed.), *Biomaterials for Skin Repair and Regeneration* (pp. 3-25): Woodhead Publishing.

Preston, J. (2012). *What Are Computers (If They're not Thinking Things)?*. In Cooper S.B., Dawar A., Löwe B. (eds) How the World Computes. CiE 2012. Lecture Notes in Computer Science, 7318. Berlin, Heidelberg: Springer. doi:10.1007/978-3-642-30870-3_61

Projects 2010 / KSP Jürgen Engel Architekten. (2010). (KH & L. O. Stapler Eds.). Braunschweig: Ruth Printmedien GmbH.

Rajkumar, R., Lee, I., Sha, L., & Stankovic, J. (2010). Cyber-physical systems: The next computing revolution. *Proceedings of the 47th Design Automation Conference*, DAC '10 (pp. 731-736). doi: 10.1145/1837274.1837461

Ranft, F., & Frohn, B. (2004). *Natürliche Klimatisierung* [Natural climatisation]. Basel: Birkhäuser.

Raskin, V. (2015). Theory, Methodology, and Implementation of Robotic Intelligence and Communication. *Procedia Computer Science, 56*, 508-513. doi:10.1016/j.procs.2015.07.243

Reas, C., McWilliams, C., & LUST. (2010). *Form+code in design, art, and architecture* (1st ed.). New York: Princeton Architectural Press.

Ritter, A. (2007). Smart Materials in Architektur, Innenarchitektur und Design [Smart materials in architecture, interior architecture and design]. Basel: Birkhäuser - Verlag für Architektur.

Romano, R., Aelenei, L., Aelenei, D., & Mazzucchelli, E. S. (2018). What is an adaptive façade? Analysis of recent terms and definitions from an international perspective. *Journal of Facade Design and Engineering, 6*(3), 065-076. doi:10.7480/jfde.2018.3.2478

Rösing, I., Price, D. J. S., & International Council for Science Policy Studies. (1977). *Science, technology, and society: A cross-disciplinary perspective. London: SAGE Publications.*

Ross, A. M., Rhodes, D. H., & Hastings, D. E. (2008). Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. *Systems Engineering, 11*, 246-262. doi:10.1002/sys.20098

Sala, M. (1994). The intelligent envelope: The current state of the art. *Renewable Energy, 5*(5–8), 1039-1046. doi:10.1016/0960-1481(94)90131-7

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

Schittich, C., Staib, G., Balkow, D., Schuler, M., & Sobek, W. (1998). *Glasbau Atlas* [Glass construction manual]. München: Institut für internationale Architektur-Dokumentation.

Schumacher, M., Schaeffer, O., & Vogt, M.-M. (2009). *Move: dynamic components and elements in architecture*. Basel: Birkhäuser.

Schumacher, P. (2009). Parametricism: A New Global Style for Architecture and Urban Design. *Architectural Design, 79*(4), 14-23. doi:10.1002/ad.912

Senagala, M. (2006). Rethinking Smart Architecture: Some Strategic Design Frameworks. *International Journal of Architectural Computing, 4*(3), 33-46. doi:10.1260/147807706778658838

Sher, E., Chronis, A., & Glynn, R. (2014). Adaptive behavior of structural systems in unpredictable changing environments by using self-learning algorithms: A case study. *Simulation-Transactions of the Society for Modeling and Simulation International, 90*, 991-1006. doi:10.1177/0037549714543090

Sobek, W., & Teuffel, P. (2001). Adaptive systems in architecture and structural engineering. *Proceedings of SPIE's 8th Annual International Symposium on Smart Structures and Materials*, 2001, Newport Beach, CA, United States. doi:10.1117/12.434141

TOC

Song, N., & Ma, Y. (2010). *Discussion on research and development of artificial intelligence.* 2010 IEEE International Conference on Advanced Management Science (ICAMS 2010), Chengdu, 2010, 110-112. doi:10.1109/ICAMS.2010.5553039

Sovacool, B. K., & Furszyfer Del Rio, D. D. (2020). Smart home technologies in Europe: A critical review of concepts, benefits, risks and policies. *Renewable and Sustainable Energy Reviews, 120*, 109663. doi:10.1016/j.rser.2019.109663

Stake, R. E. (2005). *Multiple Case Study Analysis.* New York: Guilford Publications.

Statik. (n.d.). In *Duden online.* Retrieved August 07, 2019 from https://www.duden.de/node/172919/revision/172955

Sutherland, I. E. (1964). Sketchpad a Man-Machine Graphical Communication System. *SIMULATION, 2*(5), R-3-R-20. doi:10.1177/003754976400200514

Tekic, Z., & Koroteev, D. (2019). From disruptively digital to proudly analog: A holistic typology of digital transformation strategies. *Business Horizons, 62*(6), 683-693. doi:10.1016/j.bushor.2019.07.002

Terzidis, K. (2006). *Algorithmic architecture* (1st ed.). Amsterdam ; Boston: Architectural Press.

Toro, C., Barandiaran, I., & Posada, J. (2015). A Perspective on Knowledge Based and Intelligent Systems Implementation in Industrie 4.0. *Proceedings of Knowledge-Based and Intelligent Information & Engineering Systems 19th Annual Conference*, KES-2015, Singapore, September 2015, 60, 362-370. doi:10.1016/j.procs.2015.08.143

Trummer, P. (2011). Associative Design: From Type to Population. In A. Menges & S. Ahlquist (Eds.), *Computational Design Thinking* (pp. 179-197). London: Wiley.

Turing, A. M. (1950). I.—COMPUTING MACHINERY AND INTELLIGENCE. *Mind, LIX*(236), 433-460. doi:10.1093/mind/LIX.236.433

van den Dobbelsteen, A., van Timmeren, A., & van Dorst, M. (2009). *Smart Building in a Changing Climate.* Amsterdam: Techne Press.

Verma, P. K., Verma, R., Prakash, A., Agrawal, A., Naik, K., Tripathi, R., . . . Abogharaf, A. (2016). Machine-to-Machine (M2M) communications: A survey. *Journal of Network and Computer Applications, 66*, 83-105. doi:10.1016/j.jnca.2016.02.016

Wang, L., Torngren, M., & Onori, M. (2015). Current status and advancement of cyber-physical systems in manufacturing. *Journal of Manufacturing Systems, 37*, 517-527. doi:10.1016/j.jmsy.2015.04.008

Wang, Y., & Zatarain, O. A. (2018). Design and Implementation of a Knowledge Base for Machine Knowledge Learning. *2018 IEEE 17th International Conference on Cognitive Informatics & Cognitive Computing (ICCI*CC)*, Berkeley, CA, 2018, 70-77. doi:10.1109/ICCI-CC.2018.8482034

Wegner, P., & Goldin, D. (2003). Computation beyond turing machines. *Communications of the ACM*, 46(4), 100–102. doi:10.1145/641205.641235

Weiss, K.-D. (2010). *Gatermann + Schossig: Raum Kunst Technik* [Gatermann + Schossig: Space Art Technology]. Basel: Birkhäuser.

Weyer, S., Schmitt, M., Ohmer, M., & Gorecky, D. (2015). Towards Industry 4.0 - Standardization as the crucial challenge for highly modular, multi-vendor production systems. *15th IFAC Symposium on Information Control Problems in Manufacturing,* INCOM 2015, 48, 579-584. doi:10.1016/j.ifacol.2015.06.143

Wiedermann J. (2012) On the Road to Thinking Machines: Insights and Ideas. In: Cooper S.B., Dawar A., Löwe B. (eds) *How the World Computes.* CiE 2012. Lecture Notes in Computer Science, vol 7318. Springer, Berlin, Heidelberg. doi:10.1007/978-3-642-30870-3_74

Wigginton, M., & Harris, J. (2002). *Intelligent Skins.* Oxford: Butterworth-Heinemann.

Winterstetter, T., & Sobek, W. (2013). Innovative and energy-efficient Façade technology for the KfW Westarkade Highrise in Frankfurt/Main. *Stahlbau, 82*, 35-46. doi:10.1002/stab.201390076

Wolf, M. (2012). Chapter 1 - Embedded Computing. In M. Wolf (Ed.), *Computers as Components* (Third Edition) (pp. 1-50). Boston: Morgan Kaufmann.

Wong, J. K. W., Li, H., & Wang, S. W. (2005). Intelligent building research: a review. *Automation in Construction, 14*, 143-159. doi:10.1016/j.autcon.2004.06.001

Woodbury, R. (2010). *Elements of parametric design.* London ; New York, NY: Routledge.

Xu, H., Yu, W., Griffith, D., & Golmie, N. (2018). A Survey on Industrial Internet of Things: A Cyber-Physical Systems Perspective. *IEEE Access, 6*, 78238-78259. doi:10.1109/ACCESS.2018.2884906

Yang, J., & Peng, H. (2001). Decision support to the application of intelligent building technologies. *Renewable Energy, 22*(1–3), 67-77. doi:10.1016/S0960-1481(00)00085-9

Yang, S., & Chen, Y. (2013). The M2M Connectivity Framework: Towards an IoT Landscape. *2013 IEEE International Conference on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing*, Beijing, 2013, pp. 572-579. doi:10.1109/GreenCom-iThings-CPSCom.2013.108

Yaqoob, I., Ahmed, E., Hashem, I. A. T., Ahmed, A. I. A., Gani, A., Imran, M., & Guizani, M. (2017). Internet of things architecture: Recent advances, taxonomy, requirements, and open challenges. *IEEE wireless communications, 24*(3), 10-16. doi:10.1109/MWC.2017.1600421

Yiannoudes, S. (2016). *Architecture and adaptation: from cybernetics to tangible computing*. New York: Routledge, Taylor & Francis Group.

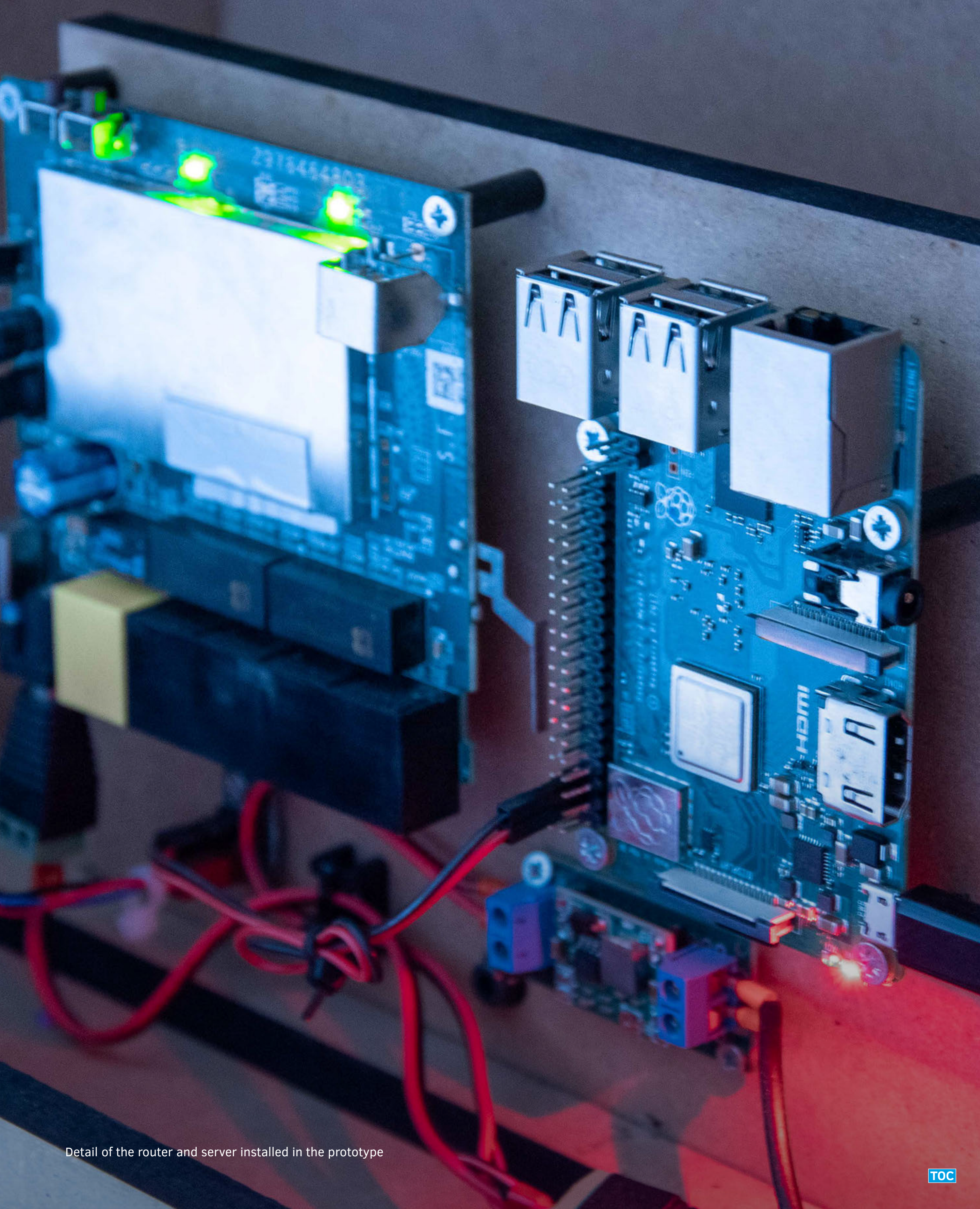
Yin, R. K. (2017). *Case Study Research and Applications: Design and Methods* (6th edition ed.). Los Angeles: Sage Publications Ltd.

Yu, L., Kin-Fai, T., Xiangdong, Q., Ying, L., & Xuyang, D. (2017). Wireless Mesh Networks in IoT networks. *2017 International Workshop on Electromagnetics: Applications and Student Innovation Competition*, London, 2017, pp. 183-185. doi:10.1109/iWEM.2017.7968828

Zacchia Lun, Y., D'Innocenzo, A., Smarra, F., Malavolta, I., & Di Benedetto, M. D. (2019). State of the art of cyber-physical systems security: An automatic control perspective. *Journal of Systems and Software, 149*, 174-216. doi:10.1016/j.jss.2018.12.006

Zaera-Polo, A., Trüby, S., Koolhaas, R., Boom, I., & AMO Harvard Graduate School of Design. (2014). *Façade*. (Elements. a series of 15 books accompanying the exhibition elements of architecture at the 2014 Venice Architecture Biennale.)

Zhaoguang, H. (1999). Intelligent space. *FUZZ-IEEE'99. 1999 IEEE International Fuzzy Systems. Conference Proceedings (Cat. No.99CH36315)*, Seoul, South Korea, 1999, 3, 1621-1625. doi:10.1109/FUZZY.1999.790147



Detail of the router and server installed in the prototype

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Curriculum Vitae

1984	Born in Steinheim (Westfalen), Germany
2008	Traineeship at UNstudio, Amsterdam
2009	Bachelor of Arts in Architecture at Ostwestfalen-Lippe University of Applied Sciences
2009	BDA Masters Award
2012	Master of Arts in Architecture at Münster University of Applied Sciences
2012 - 2015	Coordinator of the postgraduate Master of Computational Design and Construction at Werkstatt Emilie GmbH
2013 - 2016	Research associate at Ostwestfalen-Lippe University of Applied Sciences as Coordinator of the ConstructionLab
2014 - 2020	Member of the Architectural Façades and Products research group at TU Delft
2016	Lectureship at the Cologne University of Applied Sciences
2016 - 2019	Research associate at Cologne University of Applied Sciences

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Bibliography

Böke, J., Knaack, U., & Hemmerling, M. (2020). Prototype of a cyber-physical façade system. *Journal of Building Engineering*, 101397. doi:10.1016/j.jobe.2020.101397

Böke, J., Knaack, U., & Hemmerling, M. (2020). Automated adaptive façade functions in practice - Case studies on office buildings. *Automation in Construction, 113*, 103113. doi:10.1016/j.autcon.2020.103113

Boeke, J., Knaack, U., & Hemmerling, M. (2019). Superposition matrix for the assessment of performance-relevant adaptive façade functions. *Journal Of Facade Design And Engineering*, 7(2), 1-20. doi:10.7480/jfde.2019.2.2463

Böke, J., Knaack, U., & Hemmerling, M. (2018). State-of-the-art of intelligent building envelopes in the context of intelligent technical systems. *Intelligent Buildings International*, 1–19. doi:10.1080/17508975.2018.1447437

Böke, J. (2018). Computation in Architecture: Potential and Challenges for Research and Education. In M. Hemmerling & L. Cocchiarella (Eds.), *Informed Architecture* (S. 105–113). Cham: Springer International Publishing.

Hemmerling, M., Nether, U., & Böke, J. (2018). SunSys. In M. Hemmerling & L. Cocchiarella (Eds.), *Informed Architecture* (S. 129–138). Cham: Springer International Publishing.

Schindler, C., Hemmerling, M., Böke, J., Sotomayor, M., Velasco, R., Günther, P., & Allahdin, K. (2018). Moebius. In M. Hemmerling & L. Cocchiarella (Eds.), *Informed Architecture* (S. 163–168). Cham: Springer International Publishing.

Knaack, U., Pottgiesser, U., Böke, J., Ernst, M., Hildebrand, L. & Ashour, A. (2016). *Prototyping efnMobile*. Rotterdam: Nai010 Publishers.

Pottgiesser, U, Hemmerling, M & Böke, J. (Eds). (2015). facade2015. *Proceedings of the conference facade2015-Computational Optimisation*. Detmold: HS OWL, Detmolder Schule für Architektur und Innenarchitektur.

Böke, J. (2014). ThinkingSkins – towards intelligent acting façades. *Proceedings of Facade 2014 - Conference on Building Envelopes*, Lucerne: Lucerne University of Applied Sciences and Arts

Hemmerling, M., & Böke, J. (2014). *SunSys - A Case Study on Geometric Complexity in Computational Design*. Paper presented at the 16th International Conference on Geometry and Graphics, Innsbruck, 2014.

Knaack, U., Pottgiesser, U & Böke, J. (Eds). (2013). facade2013. *Proceedings of the conference facade2013 Design vs. Development.* Detmold: HS OWL, Detmolder Schule für Architektur und Innenarchitektur.

Hemmerling, M., Böke, J., & Püchner, F. (2013). Digital Design and Construction. In U. Pottgiesser & H. Strauß (Eds.), *Product Development and Architecture: Visions/ methods/innovations* (pp. 140-147). Basel: Birkhäuser.

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20#08

ThinkingSkins

Cyber-physical systems as foundation for intelligent adaptive façades

Jens Böke

New technologies and automation concepts emerge in the digitalization of our environment. This is, for example, reflected by intelligent production systems in Industry 4.0. A core aspect of such systems is their cyber-physical implementation, which aims to increase productivity and flexibility through embedded computing capacities and the cooperation of decentrally networked production plants. This development stage of automation has not yet been achieved in the current state-of-the-art of façades. Being responsible for the execution of adaptive measures, façade automation is part of hierarchically and centrally organised Building Automation Systems (BAS). The research project ThinkingSkins is guided by the hypothesis that, aiming at an enhanced overall building performance, façades can be implemented as cyber-physical systems. Accordingly, it addresses the research question:

How can cyber-physical systems be applied to façades, in order to enable coordinated adaptations of networked individual façade functions?

The question is approached in four partial investigations. First, a comprehensive understanding of intelligent systems in both application fields, façades and Industry 4.0, is elaborated by a literature review. Subsequently, relevant façade functions are identified by a second literature review in a superposition matrix, which also incorporates characteristics for a detailed assessment of each function's adaptive capacities. The third investigation focuses on existing conditions in building practice by means of a multiple case study analysis. Finally, the technical feasibility of façades implemented as cyber-physical systems is investigated by developing a prototype. The research project identifies the possibility and promising potential of cyber-physical façades. As result, the doctoral dissertation provides a conceptual framework for the implementation of such systems in building practice and for further research.

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