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

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Abstract
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 the 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.

Keywords
Intelligent building envelope, superposition matrix, adaptive façade, multi-functionality, intelligent technical system

1 INTRODUCTION

1.1 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, Schaeffer, & Vogt, 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, Lee, Sha, & Stankovic, 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, Jürgenhake, & Gausemeier, 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.

1.2 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, de Saldanha, Liedl, and Sager (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 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.

1.3 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.

1.4 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?

2 METHODOLOGY

The investigation is based on a literature review. It is organised into two main parts. In the first part, under section 3, 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. 1, 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.

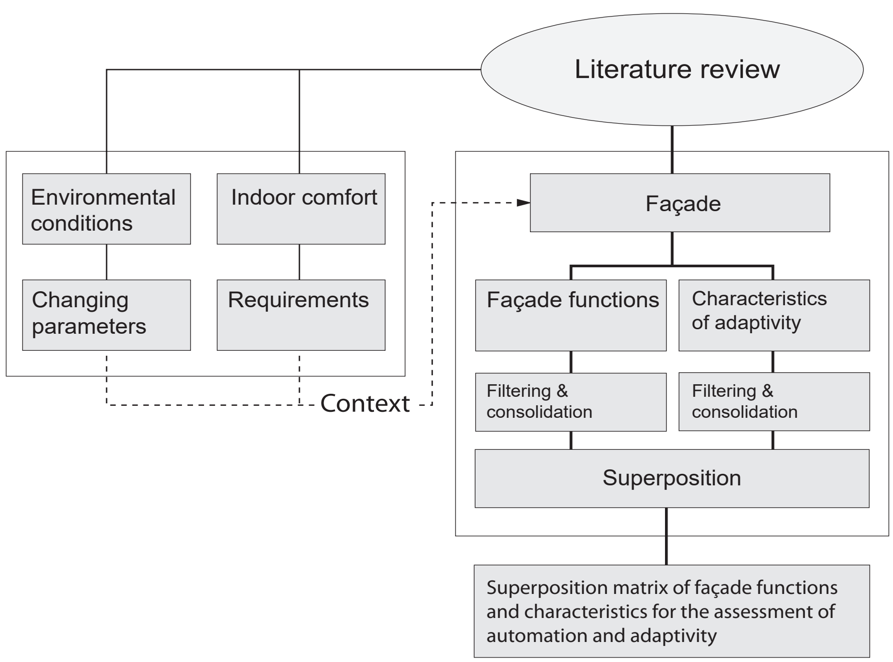

FIG. 1 Graphical abstract

A focus of the study is on the automated adaptive façade functions examined in the second part in Section 4. 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 1 of Section 4.1, 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.

FIG. 2 Schematic representation of the superposition matrix

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. 2. 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.

3 THE CONTEXT OF ENVIRONMENTAL BOUNDARY CONDITIONS AND COMFORT REQUIREMENTS

3.1 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.

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 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).

3.2 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 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, Saldanha, and Liedl (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.

3.3 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. 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 illustrates the context of the environmental conditions and comfort requirements from which the adaptive functions of the façade derive:

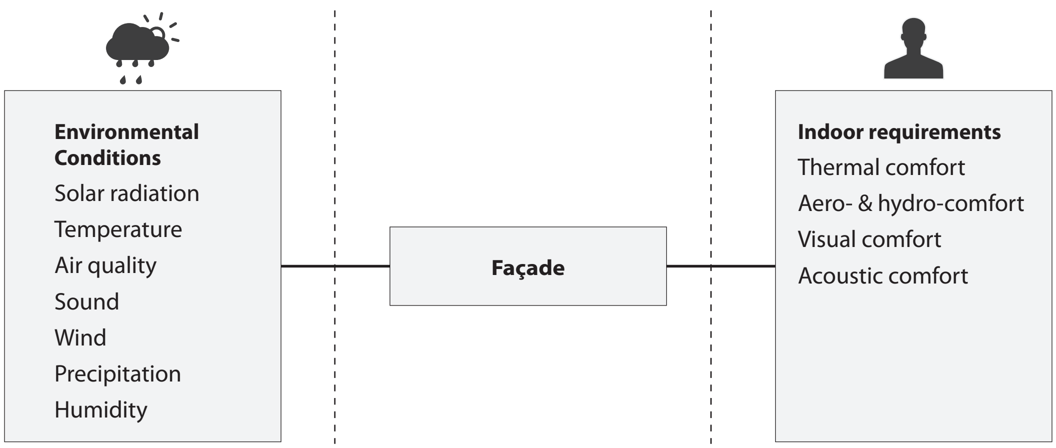

FIG. 3 Context of environmental conditions and comfort requirements

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.

4 IDENTIFICATION OF FAÇADE FUNCTIONS AND CHARACTERISTICS OF ADAPTIVITY

4.1 PERFORMANCE RELEVANT AND POSSIBLY ADAPTIVE FUNCTIONS OF THE FAÇADE

The façade has a great impact on the energy and comfort-related quality of a building. As shown in Fig. 4, 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 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, Krippner, and Lang (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”.

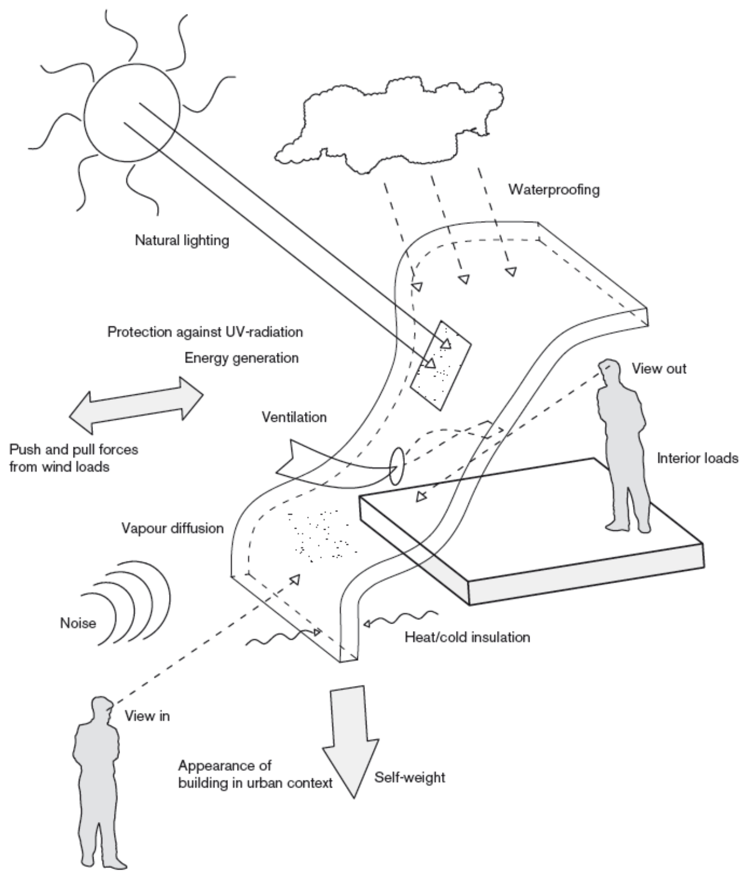

FIG. 4 Facade functions by Knaack, Klein, Bilow, and Auer (2014)

The assembly of façade functions in Table 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.

	CONSOLIDATED LIST	FILTER	ACTION		CONSOLIDATED LIST FILTERED	
					General function	**Specification**
Sun						
1	Glazing fraction	Irrelevant to an adaptive implementation	Skipped	1	**Solar** shading	
2	Shading	Specified to „Solar"	Modified			
3	Solar control glass	Specification				
4	Light deflection			2	Light deflection	
5	Glare protection			3	Glare protection	
6	Control daylight radiation			4	Control daylight radiation	*Provide a comfortable daylight level*
8	Allow natural lighting of interior	Allow to control	Modified			*Allow natural lighting of interior*
Temperature						
9	Thermal insulation			5	Thermal insulation	*Heat protection*
10	Heat insulation glass	Specification (of Thermal insulation)	Modified			*maintain indoor temperature*
11	Thermal storage mass	Irrelevant to an adaptive implementation	Skipped			
12	Decentralised 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	6	Ventilation	*Control air exchange rate*
15	Control air exchange rate	Specification				*Ventilate excessive heat*
16	Ventilate excessive heat	Specification				
User						
17	Allow visual contact	Allow to control	Modified	7	Control visual contact	*Visual contact to outside*
						Visual protection for inside
Acoustic						
18	Sound insulation	Sound insulation = reduction? Level of success		8	Sound insulation	
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			9	Generate energy	*Collect solar thermal energy*
23	Collect solar energy					*Collect solar energy*
				10	Store energy	
Supply (not dependent on outdoor climate but relevant to indoor comfort)						
24	heating	combination with cooling	Modified	11	heating and cooling	
25	cooling		Modified			
26	humidification	combination with dehumidification	Modified			
27	dehumidification		Modified	12	de- / humidification	
28	electricity			13	electricity	
29	artificial light			14	artificial light	
30	communication			15	communication	

TABLE 1 Development of the consolidated and filtered list of façade functions

In addition, the functions are filtered as shown in Table 1 in consideration of the environmental factors and requirements identified in Section 3 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.

	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

	GENERAL FUNCTION	SPECIFICATION
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	

TABLE 2 Consolidated and filtered assembly of performance-related façade functions

4.2 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 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 is a revised list of characteristics for the adaptivity of façades.

	GENERAL CRITERIA	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 adaptability	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

TABLE 3 Revised list of characteristics of adaptivity

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.

5 SUPERPOSITION OF FAÇADE FUNCTIONS AND CHARACTERISTICS OF ADAPTIVITY

In the superposition matrix shown in Table 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.

		GENERAL			BEHAVIOUR			AUTOMATION		
		Technol-ogy	Flexible	Adaptive	Operation	Response time	Degree of adaptivity	Input system	Pro-cessing 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									

TABLE 4 Superposition matrix

6 EXAMPLE FOR THE APPLICATION OF THE SUPERPOSITION MATRIX

Table 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 5. Characteristics which cannot be determined due to missing data are marked with N.A. (González, Holl, Fuhrhop, & Dale, 2010; Winterstetter & Sobek, 2013)

		GENERAL			BEHAVIOUR			AUTOMATION		
		Technol-ogy	Flexible	Adaptive	Operation	Response time	Degree of adaptivity	Input system	Pro-cessing 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	Inter-mediate space	Yes	Yes	Extrinsic	N.A	gradual	Yes	Yes	Yes
Air										
7	Ventilation	Ventila-tion flaps	Yes	Yes	Extrinsic	N.A	Active- In-active	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

TABLE 5 Superposition matrix applied to the façade of the KFW Westerkade

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 function of sound insulation is fulfilled by the intermediate space of the double façade. 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.

7 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 2.3, 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.

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