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SYSTEMATIC CLASSIFICATION OF ADAPTIVE FAÇADES – PREPARING A DATABASE

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ABSTRACT

Adaptive façades (AF) present a promising approach to reduce environmental impacts in the Architecture, Engineering, and Construction sector. However, the automatization of the façade produces new challenges as the complexity of the system increases. To support the early phase of interdisciplinary development, solution collections such as databases are helpful. Previous research identified that existing solution collections of AF do not meet the requirements that such a method demands. In the effort to develop an optimized database, this paper investigates how the state of the art can be structured in terms of content in order to present it in the database. Here, a set of design parameters is developed based on identified requirements and on the main characteristics of AF that were previously elaborated. This set offers a comprehensive perspective on the previously realized functions and mechanisms of AF and can also contribute to finding creative solutions in the form of new concepts by combining the design parameters in new ways. Finally, 40 case studies of previously implemented adaptive façades are used to evaluate the set of design parameters.

Keywords: Adaptive façades, Design methods, Early design phases, Design to X, Database

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1 INTRODUCTION AND MOTIVATION

The sector of façade engineering is important when it comes to slowing down climate change. This is because the performance of a façade has a great impact on the energy consumption of a building (IEA, 2013), as any façade performance deficits have to be compensated through operation of the technical building equipment (HVAC). Currently, heating, cooling, and lighting account for approx. 70% of the total energy consumption of residential buildings (Eurostat, 2021). Accordingly, the current static behavior of conventional façades is unable to dampen the dynamic environmental effects sufficiently and, as such, stabilize comfort levels (temperature, lighting, indoor air quality, etc.) in a building. This brought about the approach of using adaptive façades (AF), which are façades that can adapt their properties according to changing environmental conditions. The aim of these is to reduce the need for technical building equipment and, therefore, energy consumption (Loonen et al., 2014). The adaption of the façade can be realized in different ways, but most often sensors, actuators, and a control unit are integrated to regulate and adjust multiple properties of the façade. The disadvantage of these types of façades is that they are more complex, which produces additional challenges during the design phase, as well as over the entire lifecycle of the AF (Voigt et al., 2021a). To compensate this, Voigt et al. (2023) developed a lifecycle framework for AF, considering all the lifecycle phases and stakeholders involved, in order to gain a comprehensive perspective on the task of designing AF. They state that, during the early stages of the lifecycle, design requirements are identified for the basic evaluation phase, and then suitable AF solutions are sought on the market. Here, a database/solution collection of already built AF can support the search for suitable adaptive (reference) façades (Voigt et al. 2022). But when reviewing the current literature, there is no suitable database/solution collection developed yet. Existing databases/solution collections are mostly focused on specific aspects of AF, or consist only of image collections without in-depth information. Therefore, this article systematically addresses the topic with the objective to analyze the current state of the art of AF, and to find a suitable structure in which to organize the different AF in a database. The corresponding research question to be answered is: *How can the current state of the art of AF be classified for integration into a database?*
The following requirements can be raised to the classification approach according to known literature:

1. AF-specific characteristics should be used as classification criteria (VDI, 1982) which ideally describe the product well.
2. The classification and the corresponding criteria need to be consistent (VDI, 1982).
3. The criteria that classify and describe the content need to be independent of each other, or the dependency must be described (Feldhusen and Grote, 2013).
4. Initial completeness regarding content and classification approach (Feldhusen and Grote, 2013, p. 377; VDI, 1982, p. 4).

2 METHODOLOGY AND RESEARCH APPROACH

Based on the research objective and the requirements presented in the previous section, a two-stage research methodology can be derived. First, the criteria of the solution space of the current state of the art of AF are defined and then an evaluation based on 40 existing case studies is carried out. With respect to the first step of creating the classification criteria, it is appropriate to build on the main characteristics of AF developed in Voigt et al. (2022), as these were systematically compiled from the analysis of 47 classification approaches from the literature and have already been evaluated for initial completeness as well as consistency and logic. Additionally, the main characteristics already serve as a basis for identifying suitable design goals and requirements for the AF project. It is therefore considered helpful if the requirements that are specified on the basis of these main characteristics can be directly assigned to the corresponding solutions/content in the database (see Figure 1).

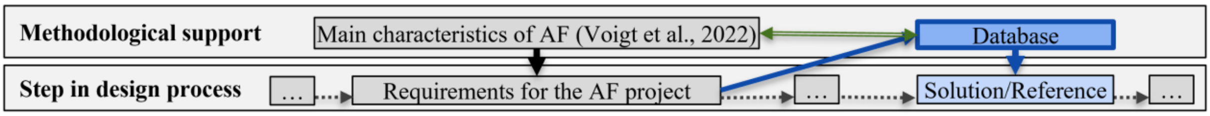


Figure 1: Logic of this research in the AF design process according to Voigt et al. (2023)

However, the main characteristics are constrained to characteristics that are specific to AF projects. Therefore, they represent a partial set of the relevant criteria. Aspects such as costs, materials, safety,

etc., are not considered here. The approach of the research is that, for clients, architects, and façade planners working with AF for the first time, the AF-specific characteristics cause particular uncertainty and skepticism, which inhibits the use of the technology on a larger scale (Karanouh and Kerber, 2015; Voigt et al., 2021a).
Therefore, the main characteristics (e.g. adaption time) of AF are further deepened by adding the design parameters (e.g. seconds, minutes, etc.) that previous AF have adopted within these main characteristics. For this, Section 3 outlines a preparation step conducted to identify the dependencies of the main characteristics and to analyze and unify the existing classification approaches (see Figure 2). In Section 4, the set of derived design parameters is presented, and in Section 5, the result is evaluated by assigning 40 case studies to the design parameters. Section 6 contains the conclusion and presents possible next steps. This article is part of a research project on the refinement of design procedures for AF, and, according to the logic of the Design Research Methodology presented by Blessing and Chakrabarti (2009), contributes to a comprehensive prescriptive study.

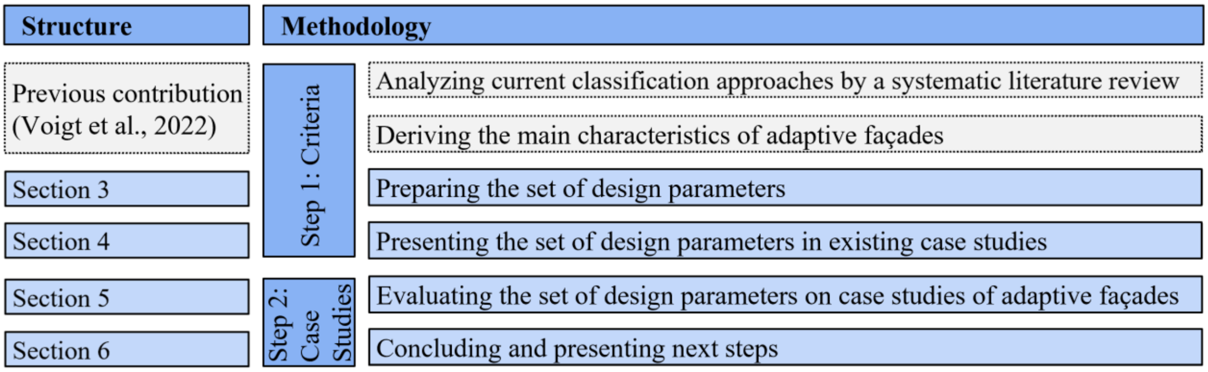


Figure 2: Research methodology and structure of the article

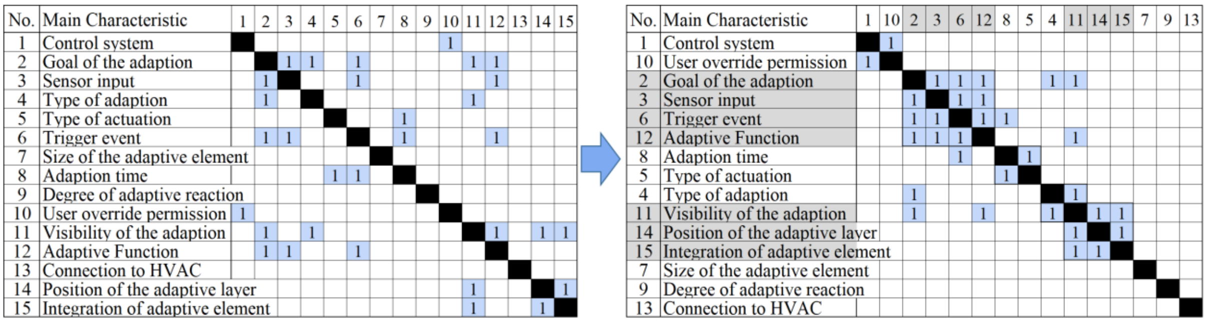
3 PREPARING THE SET OF DESIGN PARAMETERS

In Voigt et al. (2022), 47 classification approaches for AF were identified. Each of them describes some of the main characteristics of AF, but contains gaps in terms of number and description. In order to achieve a consistent and more complete set of design parameters (see requirements in Section 1), the criteria from the literature must first be analyzed and processed.

3.1 Analyzing the dependencies between the main characteristics

In accordance with the requirements raised in the first section, a dependency analysis is performed based on the main characteristics identified by Voigt et al. (2022). This reveals the correlations between the main characteristics and helps to simplify a subsequent consistency check. In the following, all of the main characteristics except for the "performance impact" are considered. Although this plays a decisive role in the definition of requirements, it is almost impossible to obtain any reliable (mostly quantitative) information from publications and images of AF for the creation of a database. Furthermore, this main characteristic has only been mentioned by one source in the previous analysis by Voigt et al. (2022). The division into "minor," "medium," "variable," and "significant" described by Basarir (2017) also offers only little added value in the context of the solution set of the design parameters to be developed in this article. The dependencies of the remaining 15 main characteristics can be identified by comparing the descriptions of the design parameters already assigned in the literature. For example, there is a dependency between the "goal of the adaption" and the "sensor input," as the goal of improving thermal comfort requires, for example, temperature sensors. All of the main characteristics are analyzed in a similar manner to this example and their dependencies are presented in Table 1 (left side). Based on the optimization algorithms from Pimmler and Eppinger (1994) and Laufer et al. (2020), the criteria are reorganized into clusters, which can be seen on the right side. In addition to dependencies of individual criteria, two major clusters can be identified in particular. The first consisting of "goal of adaptation," "sensor input," "trigger event," and "adaptive function," and the second consisting of "visibility of the adaption," "position of the adaptive layer," and "integration of adaptive element." There are also three characteristics that show no direct dependencies.

Table 1: Deriving the dependencies between the main characteristics identified in Voigt et al. (2022).



No.	Main Characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Control system	■									1					
2	Goal of the adaption		■	1	1		1					1	1			
3	Sensor input		1	■			1						1			
4	Type of adaption		1		■							1				
5	Type of actuation					■			1							
6	Trigger event		1	1			■		1				1			
7	Size of the adaptive element							■								
8	Adaption time					1	1		■							
9	Degree of adaptive reaction									■						
10	User override permission	1									■					
11	Visibility of the adaption		1		1							■	1		1	1
12	Adaptive Function		1	1			1						■			
13	Connection to HVAC													■		
14	Position of the adaptive layer											1			■	1
15	Integration of adaptive element											1			1	■

No.	Main Characteristic	1	10	2	3	6	12	8	5	4	11	14	15	7	9	13
1	Control system	■	1													
10	User override permission	1	■													
2	Goal of the adaption			■	1	1	1			1	1					
3	Sensor input			1	■	1	1									
6	Trigger event			1	1	■	1	1								
12	Adaptive Function			1	1	1	■				1					
8	Adaption time					1		■	1							
5	Type of actuation							1	■							
4	Type of adaption			1						■	1					
11	Visibility of the adaption			1			1			1	■	1	1			
14	Position of the adaptive layer										1	■	1			
15	Integration of adaptive element										1	1	■			
7	Size of the adaptive element													■		
9	Degree of adaptive reaction														■	
13	Connection to HVAC															■

3.2 Preparing and unifying the design parameters

After the dependencies between the criteria are identified, the 47 papers from the systematic literature research in Voigt et al. (2022) are reviewed again to identify the design parameters described there. To achieve a solution set of design parameters based on the main characteristics, the descriptions from the literature are compared and similarities and contradictions are identified. In many cases, the solution set can be formed by adding all possible solutions together and choosing appropriate terms, so that they are all described with the same logic.

In contrast, descriptions about the "adaptive function" of AF are particularly contradicting. According to Pahl et al. (2007), a function is defined as a *"general and intended relation between input and output of a system with the purpose of accomplishing a task."* In this respect, the function of a system is based on the flows of energy, material, or signals/information (Ehrlenspiel and Meerkamm, 2017). When considering the façade as the system of interest, the input to the system is a combination of the user (comfort) requirements and the environmental influences on the building (wind, solar radiation, precipitation, etc.). The behavior of the façade then adapts to meet the requirements of the occupants and therefore performs an operation on the flow of energy, material, or signal/information that passes through the AF (see Table 2).

When comparing this knowledge from the area of product development (Mechanical Engineering) to the current literature on AF functions (Architectural Façade Engineering), several descriptions are considered unsuitable, as they describe the function of the façade as "ventilation," "electricity," "communication," (Böke et al., 2020; Kuru et al., 2019), or "glare protection," "wind loads," or "cooling" (Heusler, 2013). Nevertheless, the intended functionality of the AF is in line with the other publications in which the functions are described with operations similar to the logic of Pahl et al. (2007). A comparison of the operations of these publications is presented in Table 2. As the different descriptions mainly address the same functions, but use different operations/terms, it is checked how a consistent and simple set of operators could be developed. For this, also the fundamental functions according to Pahl et al. (2007) are considered (see Table 2).

Table 2: Comparing the operations of the functions of AF (Loonen et al., 2015; Lopez et al., 2015; Basarir, 2017; Taveres-Cachat et al., 2019) with the metric by Pahl et al. (2007)

Loonen et al. (2015) Basarir et al. (2017)	Taveres-Cachat et al. (2019)	Lopez et al. (2015)	Pahl et al. (2007)
• *Convert*	• *Convert*	• *Evaporate*	• *Convert*
• *Change* • *Modulate*	• *Modulate* • *Buffer* • *Distribute* • *Recover*	• *Modulate* • *Exchange* • *Dissipate* • *Diffuse*	• *Change*
• *Store* • *Collect*	• *Store* • *Conserve*	• *Absorb* • *Collect* • *Gain* • *Conserve*	• *Store*
• *Prevent* • *Reject*	• *Prevent*	• *Filter* • *Reflect* • *Redirect*	• *Separate (neg.: connect)*
• *Admit*	• *Promote*		• *Conduct*

As can be seen in Table 2, several synonyms for similar operations are currently used. The reason for this is that every flow of energy, material, or signal/information has its own set of operations. For example, Lopez et al. (2015) assign *absorbing*, *collecting*, and *evaporating* solely to *humidity*, and regulating *temperature* is described through *dissipating*, *gaining*, and *conserving*. This variety is not considered necessary and therefore it is proposed to reduce the number of operations and apply the logic of Pahl et al. (2007). When combined with the corresponding flows of energy, materials, and signals/information correlated with AF (Loonen et al., 2015; Lopez et al., 2015; Basarir, 2017; Taveres-Cachat et al., 2019), the AF functions can be described as shown in Figure 3:

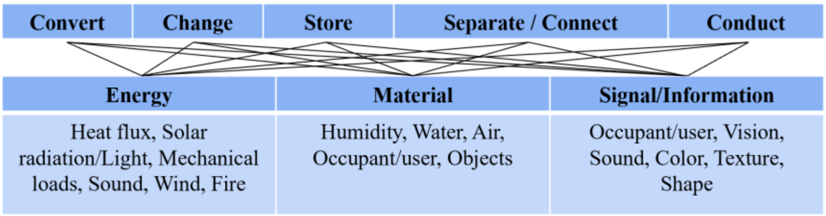


Figure 3: Describing the possible AF functions according to the logic of Pahl et al. (2007)

Based on the dependency analysis from the previous section, the collected set of design parameters from the literature can be checked for consistency and subsequently extended (see Figure 4). The extension of the set of design parameters is enabled because each *design parameter (e.g. Ax)* within a **main characteristic A**, interacts with at least one *design parameter (e.g. Bx)* of a dependent second **main characteristic B**. Thus, if there are no associated parameters under the **main characteristic B** for the design parameters under the **main characteristic A** *(e.g. Ay)* in the existing descriptions from the literature, this initiates a search to uncover these dependencies and identify *design parameter Bx* (or even several) and include them in the collection.

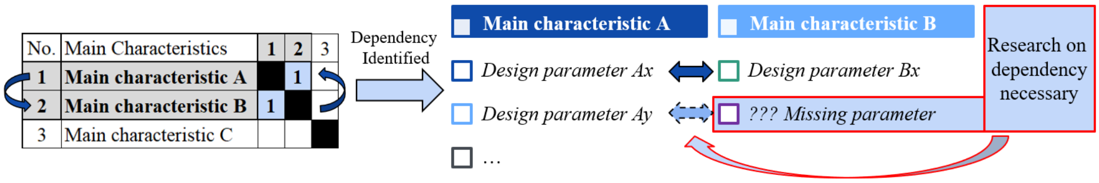


Figure 4: Extension of the identified design parameters due to consistency

An example is given with *thermal comfort* (**goal of the adaption**). Here, data is analyzed to determine which flows of energy, material, or signals/information can be adjusted to address *thermal comfort (design parameter Ax)* in the building. According to DIN EN ISO 7730 (EN ISO 7730, 2005), the parameters influencing thermal comfort are heat radiation from the floor and walls, the temperature of the air inside the room, and the speed of the air. When this data is mapped to the façade, the following parameters are relevant: *heat flux through the façade, solar radiation through the façade, and ventilation or openings enabling airflow (design parameters Bx)*. In other words – using the terminology from the above function description – it is about *changing* the level of *conductivity* with respect to *heat flux*, *solar radiation/light*, and *air*. This insight can now be compared with the descriptions of the AF functions in the literature, and thus the solution set can be expanded in terms of its consistency. All the other main characteristics and design parameters can be compared to one another in a similar way to this example.

4 SOLUTION SET OF DESIGN PARAMETERS IN EXISTING CASE STUDIES

Based on the dependency analysis and the process of preparing the design parameters, the following solution set of design parameters can be derived (see Table 3). Most of the design parameters can be identified through analysis of the literature. Criteria that were added with respect to consistency according to the description of the previous section are underlined in Table 3. In addition to Table 3, in the following, the design parameters and descriptions are briefly introduced. The **control system** describes how the façade is controlled. A distinction can be made between self-adapting behaviors programmed into the material (*intrinsic*) and adaptation by a separate control system with an additional energy need (*extrinsic*), in which the information determined by the sensors is processed and the reaction is then generated by actively controlled actuators (Loonen et al., 2015). The **user override permission** – the ability of the user to influence the control strategy – depends on the setup of the control system and whether it is immutable programmed into the material (Mols et al., 2017; Taveres-Cachat et al., 2019). The **goal of the adaption** describes what is to be achieved by adapting the properties of the façade. Here, different comfort aspects , such as *thermal comfort, indoor air quality, visual comfort, or acoustic quality* (Loonen et al., 2015; Kuru et al., 2019), can be addressed. *Visual comfort* includes, in particular, the lighting but also privacy and visibility through the façade. *Energy generation, interaction with humans* (Loonen et al., 2015), *aesthetics, lightweight design*, or increased *protective properties* (earthquake, fire, etc.) can also be reasons for making the façade adaptable. At this point, only goals that can primarily be achieved by the AF are considered. Secondary effects such as reduced environmental impacts in the construction, as presented by Borschewski et al. (2023), are not considered here.

Table 3: Solution set of design parameters of AF derived and further developed (parameters added for consistency are underlined)

Main Characteristic	**Set of Design Parameters**										
Control System	Extrinsic	Intrinsic									
Goal of the adaption	Thermal comfort	Indoor air quality	Visual comfort	Acoustic quality	Energy generation	Interaction with humans	Aesthetics	Lightweight design	Protection		
Sensor input	None	Light	Temperature	Moisture	Magnetic fields	Electricity	Wind	Air	Sound	Picture/ Camera	Tension
Type of adaption	Change in…										
	Movement	Color	Texture	Stiffness	Transparency	Permeability	Conductivity				
	Transformation	Translation	Rotation	Scalation							
Type of actuator	Pneumatic	Hydraulic	Magnetic	Chemical	Electrical	Natural/ Biological	Thermal				
Trigger event	Ordinary events			Exceptional events							
	Temperature Precipitation Humidity Wind speed Mechanical loads	Sound Air quality Objects Occupant/User	Time/Pre-programmed Neighborhood trigger Electricity consumption Grid trigger Light/Solar radiation Glare/Sun location	Hurricane Flood Fire Earthquake Explosion							
Size of adaptive element	Building material	Façade element	Façade component	Façade system/ Wall	Building envelope/ Whole building						
Adaption time	Seconds	Minutes	Hours	Day-Night	Seasons	Years	Decades				
Degree of adaptive reaction	Binary (on/off)	Gradual									
User override permission	Yes	No									
Visibility of the adaption	Visible	Not visible									
Adaptive function **Operation**	Change	Conduct	Store	Convert	Separate	Connect					
Flow	**Energy:** Heat flux, Sound, Solar radiation/Light, Mechanical loads, Wind, Fire		**Material:** Humidity, Water, Air, Occupant/User, Objects		**Signal/Information:** Occupant/User, Vision, Sound, Color, Texture, Shape						
Position of the adaptive layer	External	In between	Internal								
Connection to HVAC	None	Air	Fluid	Electricity							
Integration of adaptive element	Additional	Replacing									

Depending on the goal of the adaption, the AF behavior is designed to fulfill different **adaptive functions**. These can be described with several operations (*change, conduct, store*, etc.) that are carried out on several possible flows of *energy, material,* or *signals/information* (see Section 3.2). Of course, in terms of an extrinsic AF, it is necessary to measure different parameters with sensors. For example, the **sensor input** could be the *lighting* inside or outside the building (Matin and Eydgahi, 2019). *Temperature, moisture* (Matin et al., 2017), *magnetic fields, electricity* (Matin and Eydgahi, 2019), *wind* (Böke et al., 2020), *air* (Taveres-Cachat et al., 2019), *sound*, or *pictures* can also be used as input. Furthermore, in the case of protective functions, the *tensions* within the façade structure could be measured, and in the case of intrinsic or pre-programmed systems, it is also possible to use *no sensors* at all (Böke et al., 2020). Linked to the parameter to be measured, the **trigger event** also plays a role. The adaptation can be triggered either by *ordinary* scenarios (Bedon et al., 2019), such as *temperature* changes, *precipitation* (Soudian and Berardi, 2021), or the *user* (Yoon, 2018), or by *exceptional* events (Bedon et al., 2019), such as a *hurricane, flood, fire, earthquake*, or an *explosion*. If the façade subsequently adapts to such an event, the properties of the façade will change. Here, several **types of adaption** can be distinguished, such as a change in *transparency*, *color*, *stiffness* (Yoon, 2018; Bedon et al., 2019), or *texture* (Basarir, 2017). Different types of *movement* (Basarir, 2017) made by the AF can also be identified, such as *transforming*, *translating*, *rotating*, or *scaling*. In this respect, the **adaption (time)** can be realized in a matter of *seconds*, *minutes*, *hours*, or *days*, and in some cases, even longer periods of time are focused on, such as *seasonal changes* (Loonen et al., 2015).

Focusing on the **type of actuator**, the AF can be actuated for example with *pneumatic*, *hydraulic* (Basarir, 2017), or *magnetic* (Addington and Schodek, 2005) actuators. *Chemical* (Addington and Schodek, 2005), *electrical* (Gosztonyi, 2018), *natural/biological* (Addington and Schodek, 2005), or *thermal* (Al-Obaidi et al., 2017) actuators are also possible. Although this categorization naturally applies to extrinsically controlled façades, it is also applicable to the actuators of an intrinsically actuated façade (e.g. shape memory alloys). Other AF characteristics describe the (greatest yet implemented) **size of the adaptive element**, which can range from single materials (mostly low technology readiness level), façade *elements* (the size of a door handle), façade *components* (such as fenestrations), to a *whole façade system/wall* (Basarir, 2017) or even a *building envelope/whole building* (Tabadkani et al., 2021) that also covers the roof. The size and the **position of the adaptive layer** – *external, in between existing layers, or internal* (Gosztonyi, 2018) – affects the **visibility of the adaption** to varying degrees (Basarir, 2017). This often also goes hand-in-hand with the **integration of the adaptive element** into the building, as some AF are installed in *addition* to a façade that would also work independently and some are integrated into the existing façade, *replacing* the previous one (Soudian and Berardi, 2021). Independent of this is the **connection** of the AF **to** the **HVAC** where, for example, connections for *water*, *air* (Heiselberg, 2009), or *electricity* lines must be planned (intrinsic control also works without any connection) and also the **degree of the adaptive reaction**, which can be *binary* or *gradual* (Loonen et al., 2015).

5 EVALUATING THE SET OF DESIGN PARAMETERS ON CASE STUDIES OF ADAPTIVE FAÇADES

In order to evaluate the set of design parameters, different AF case studies are assigned to the logic from Table 3. In this way, it is possible to check whether the presented collection of parameters is consistent with the state of the art. This check is necessary because the set of design parameters is currently based on the classifications of existing literature and the own extension is based on the dependency analysis in Section 3.1. As can be seen in Figure 5, the analysis of 40 AF case studies based on the solution set of design parameters provides initial insights into the current state of the art. The frequency of every design parameter is shown after the parameter description, and the order of the parameters is based on the frequency with which they are mentioned. The case studies were found through conducting an online search and through consideration of the papers already worked with in previous publications.

Accordingly, no attempt was made to find a specific type of AF that would influence the representation of the numbers in Figure 5. Nevertheless, it can be seen that, by considering the case studies from existing classification approaches (Aelenei et al., 2018; Böke et al., 2020; Hafizi and Vural, 2022), especially AF with a high Technology Readiness Level were considered. In other words, AF that have mostly already been implemented as an entire façade system (29 out of 40). To explain the numbers presented in the Figure, it must be mentioned that within a category, double entries are possible if different adaptive technologies were implemented in the façade at the same time. Likewise, not all of the identified main characteristics are addressed equally in the literature. This results in different total numbers for each main characteristic, although the relative share of each design parameter within the main characteristic is still identifiable. It is possible to deduce that AF with a focus on adapting solar radiation (35/40) and vision (30/40) were particularly frequently represented in the sample. In this respect, the goal of the adaption is mostly to improve visual (34/40) and thermal (30/40) comfort with subsequent trigger events of solar radiation (21/40), glare (21/40), and temperature changes (13/40). As the adaption is most often achieved by actively moving shading elements in a rotational (21/40), translational (14/40), or scaling (7/40) way, the control system is extrinsic (36/40) in most cases. Furthermore, most of the time light (29/40) and temperature (11/40) sensors are used whose data is then processed to control the actuators (electrical in 25/40 cases) in a matter of minutes (29/40) or seconds (17/40) gradually (35/40) between the different states. The position of the adaptive layer is external in 27 cases and internal in 11 cases, but in nearly every case

(37/40) the adaption is visible. In many cases, the AF "layer" is applied in addition to an existing one (28/40), which might bring about further need to find ways to integrate the adaptive functions properly in the façade (Voigt et al., 2021b). Furthermore, information about user override permissions of the programmed control strategy was found in only 13 of the 40 AF. 17 of them had none. Only very little information on the connection of the AF system to the HVAC could be found. But mostly the connection was designed based on the electrical system of the building. After the sample had been assigned to the set of design parameters, it was found that none of the AFs had exhibited any further properties within the main characteristics considered here. This suggests that initial completeness has been ensured, although final completeness is not achievable.

Figure 5: Assigning 40 AF case studies to the design parameters (sorted by frequency)

6 CONCLUSION AND FURTHER STEPS

The objective of this study was to develop a metric for mapping the content of the current state of the art in AF in a database. The corresponding requirements state that the criteria to be selected should describe the product, or in this case the AF, well (VDI, 1982). This was made possible because the basis is formed by existing evaluated main characteristics, whose specificity to AF was reviewed in a previous investigation. Building on this, *consistency* of the criteria is required (VDI, 1982), which was made possible by revealing the dependencies between the criteria in Section 3.1, which was the third requirement for the metric (Feldhusen and Grote, 2013). Based on these dependencies, the collection of design parameters extracted from the literature could be further extended within the limits of *logic*. The final assignment of the case studies in Section 5 shows an *initial* degree of *completeness* in addition to a renewed *consistency* check between classification and state of the art. Furthermore, as a part of the research, the approach of fundamental functions according to Pahl et al. (2007) was transferred from the field of product development to the field of AF, in order to unify and simplify the functional descriptions of AF systems. The result presented here provides the basis for further systematic considerations in the field of AF. As a direct output, the metric can be used to create the intended database and thus to analyze and present the state of the art in a suitable way. For this, additionally formal aspects and requirements according to the visualization of the content in the database have to be raised to develop a suitable database mock-up. In addition, the set of design parameters presented here can already support the development and thus provide new and innovative approaches for AF by appropriate combination of the different parameters. For this, especially the application of fundamental functions provides a sub-solution space with high potential for innovation. Combining the different operations with the flows of energy, materials, and signals/information could bring about ideas such as storing sunlight to illuminate the street at night via fluorescence, conducting light from the façade via mirrors and glass fibers into deeper interior spaces, actively changing the wind resistance in extreme weather conditions, or improving accessibility (e.g. for the fire brigade) in the event of catastrophes (e.g. house fire). Further work could integrate the database in the workflow of an integrated design process for AF to show the interaction with possible other methods used in the early design phases.

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