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Main Characteristics of Adaptive Façades

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Abstract

Adaptive façades (AF), unlike conventional façades, respond to their environment to reduce energy consumption while increasing comfort. The planning of AF presents architects and engineers with a variety of challenges. One central challenge is the specification of the right planning goals in the early phases. This paper identifies in a systematic literature review the main characteristics which were crucial in previous realizations of AF. Due to the comprehensive approach it provides a reference for the goal definition of subsequent projects and the development of further methodical support.

Keywords: architectural design, requirements management, characteristics and properties, adaptive facades, literature review

1. Introduction and motivation

The main functional task of a façade is to separate the outside world from the inside and to protect the interior from external influences such as wind, precipitation or intense solar radiation (Herzog and Krippner, 2004). However, conventional façades are usually designed as static façades and any comfort deficits due to changing environmental conditions are compensated by the building's technical equipment (e.g. heating or air conditioning). Compared to conventional façades, adaptive façades (AF) are characterized by being adaptable to environmental changes through their adjustable properties (Attia et al., 2018). This could be done for example trough integration of sensors, actors and a control unit, regulating the amount of solar radiation or air going through the AF. Therefore, the demand for energy can be reduced, as less technical building equipment (e.g. heating-, cooling- or ventilation systems) is needed to optimize occupants' comfort (Loonen et al., 2014a).

However, Voigt et al. (2021) describe that there is still a large number of challenges before AF can be implemented on a widespread basis. Examples are the stakeholder's scepticism to new technologies, missing performance evaluation models on a building level (Loonen et al., 2013) or the definition and specification of most promising design parameters in the early design phase. The last-mentioned aspect is addressed in this contribution. It is especially challenging due to the complexity of AF (Attia, 2018b) and the high number of stakeholders needed in their planning, as stakeholders often have different requirements which must be coordinated with each other (Loonen et al., 2014b; Piroozfar et al., 2019). In addition, it is important to make correct decisions in the early phases, as they have the greatest impact on the overall development and performance of the product (Schade et al., 2011).

2. Research approach and structure of the article

In order to describe which specific design parameters (e.g. hydraulic or pneumatic actuation) have been pursued in previous implementations of AF, it is appropriate to look at existing case studies and start by analyzing their main characteristics (e.g. actuation type). As existing classifications and sets of

solutions (Basarir, 2017; Attia et al., 2018; Gosztonyi, 2018; Heidari Matin and Eydgahi, 2019; Yoon, 2020) already focus on the main characteristics of AF, their higher-level analysis provides a good basis for this research. Already carried out high-level analyses of classification approaches offer a first reference (Loonen et al., 2015; Basarir, 2017; Böke et al., 2020), but a review of them exposes gaps in their set of criteria. To obtain a more complete set of the main characteristics, the different classification approaches first have to be compiled and compared.
The aim of this paper is to generate a comprehensive set of main characteristics of AF. This will provide a basis for the identification of suitable design parameters in AF projects and also supports the future development of methodical support. Therefore, the research question to be answered in this paper is: *What are the main characteristics of adaptive façades?*
This article is part of a research project on the refinement of planning procedures for AF and is part of a comprehensive prescriptive study of the Design Research Methodology presented by Blessing and Chakrabarti (2009). To this end, Section 3 explains the research methodology used. Section 4 presents the characteristics identified in a literature review and provides a brief description of these. In Section 5, a support evaluation is conducted. A summary with a short outlook is given in Section 6.

3. Methodology

In order to achieve a comprehensive set of main characteristics, a systematic literature review has been conducted. The review involves the following four steps:

1. Identifying relevant synonyms for the terms “adaptive,” “façade,” and “classification” in German and English and using wildcards (“*”) wherever useful.
2. Conducting a literature review based on the synonyms in four electronic databases.
3. Multistage filtering of the results found (see Figure 1).
4. Detailed review of the remaining papers.

Based on the terms found in step 1, the main literature review was conducted in March 2021 on the following electronic databases: *Web of Science, Science Direct, Pro Quest* and *Wiley Online Library*.

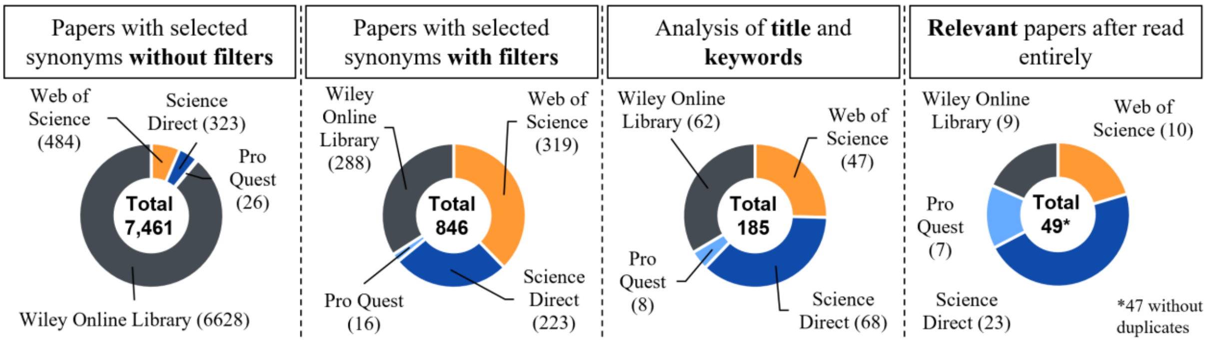

Figure 1. Results of the systematic literature review

The initial search based on the synonyms found 7,461 results (see Figure 1, left). After adjusting filters (e.g. subject area), the number of papers found dropped to 846. Further analysis of title and keywords resulted in 185 papers of interest, of which 47 proved relevant to the research question after reading the papers in completion (see Figure 1, right, without duplicates).

4. Comprehensive set of main characteristics of AF

The relevant literature contains a variety of existing classification approaches and sets of solutions for AF. Although these often include information on the associated architect or the location (Heidari Matin and Eydgahi, 2019), these boundary conditions are not included in this set, as they do not belong to the product-related design parameters on which this research is focused. In the following, the results of the literature review are presented first, followed by a description of the criteria that were found.

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4.1. Results of the literature review

The result of the analysis of the 47 relevant papers is shown in Table 1. The characteristics identified are listed horizontally, while the literature sources are listed vertically.

Table 1. Comprehensive set of main characteristics of AF

	Qualitative																								Quantitative									
Characteristics: / Literature:	Control system	Goal of the adaptation	Adaptive function	Type of adaptation	Type of actuation	Trigger event	Size of the adaptive element	Reaction/adaptation time	Technology principle	Degree of adaptive reaction	User override permission	Material	Visibility of the adaptation	Durability and reliability	Sensor input	Aesthetics	Complexity	Type of façade structure	Integration of adaptive element	Connection to HVAC	Type of façade suspension	Position of adaptive element	Degree of prefabrication	Performance impact	Costs	Safety	Environmental impact	Energy consumption	Physical properties	Number of façade layers	Weight	Installation space / thickness	User friendliness	Maintenance effort
(Addington and Schodek, 2005)	■			■	■																													
(Aelenei et al., 2016)	■	■	■				■	■	■	■			■																					
(Al Dakheel and Tabet Aoul, 2017)				■					■			■																						
(Al-Obaidi et al., 2017)		■				■																												
(Antonucci et al., 2021)		■					■			■																								
(Attia et al., 2018)							■																											
(Basarir, 2017)	■	■	■	■	■	■	■	■		■			■				■	■						■										
(Basińska, 2017)																									■		■	■						
(Battisti et al., 2019)		■		■	■							■																						
(Bedon et al., 2018)				■	■	■																												
(Bedon et al., 2019)				■	■	■																												
(Boeke et al., 2019)	■		■		■	■	■	■		■	■				■																			
(Böke et al., 2020)	■		■		■	■		■		■	■				■																			
(Fassbender et al., 2021)		■																							■		■							
(Favoino, op. 2018)																													■					
(Fox and Yeh, 2000)	■																																	
(Frighi, 2021)	■	■	■			■	■			■																								
(Gosztonyi, 2018)				■	■													■			■	■												
(Heidari Matin and Eydgahi, 2019)	■				■	■						■			■																			
(Herzog and Krippner, 2004)	■		■		■									■									■							■				
(Heusler, 2013)			■							■																								
(Heusler, 2019)	■			■			■					■																						
(Jin and Overend, 2014)		■												■											■	■	■							
(Juaristi et al., 2018)			■																															
(Juaristi et al., 2020b)																												■						
(Juaristi et al., 2020a)	■	■																											■					
(Kassem and Mitchell, 2015)		■												■		■									■	■								■
(Kumar and Raheja, 2016)																														■				
(Kuru et al., 2019)	■	■	■	■		■	■																											
(Loonen et al., 2013)	■	■						■																										
(Loonen et al., 2015)	■	■	■				■	■	■	■			■																					
(Lopez et al., 2015, p. 32)			■																															
(Mankins, 2009)																																		
(Mols et al., 2017)								■			■					■	■								■	■								
(Matin et al., 2017)	■														■																			
(Ochoa and Capeluto, 2009)		■							■																									
(Per Heiselberg, 2012)		■	■						■											■														
(Ramzy and Fayed, 2011)	■								■				■												■									
(Sobek et al., 2000)				■																														
(Soudian and Berardi, 2021)	■		■			■		■											■															
(Tabadkani et al., 2021)	■		■	■	■		■	■			■	■	■																					
(Taveres-Cachat et al., 2019)	■	■	■			■	■				■																							
(Velasco et al., 2015)	■			■																														
(Wang et al., 2012)		■																																
(Yoon, 2018)				■	■	■			■																									
(Zavadskas et al., 2013)		■									■			■		■	■								■	■	■				■	■	■	
(Zhang et al., 2015)			■	■					■																									
Counted number:	20	18	16	14	12	12	11	9	8	8	6	5	5	5	4	3	3	2	1	1	1	1	1	1	7	4	4	3	2	2	1	1	1	1

The marked cells represent the characteristics found in the literature. The identified criteria are further distinguished between qualitatively and quantitatively specified characteristics, similar to how they are presented in the literature. The last line shows the frequency with which the criteria are mentioned, with the characteristics listed in descending order from left to right according to their frequency.

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The graphical representation of the state of the literature in Table 1 exposes the gaps in the individual classification approaches. Although the research presented here was carried out systematically, its degree of completeness has to be further tested in the next section on the basis of a support evaluation.

4.2. Description of the identified characteristics

Having identified and collated the characteristics in the previous subsection, in this subsection they are introduced with a short description. Although all the criteria mentioned were analyzed from publications on AF, some of the criteria mentioned there apply to façades in general. In order to obtain a more specific set, a distinction is made between characteristics that are generally relevant for façades and those that are specific to AF (see Figure 2). Subsequently, the focus lies on specific characteristics, since they are part of the present investigation.

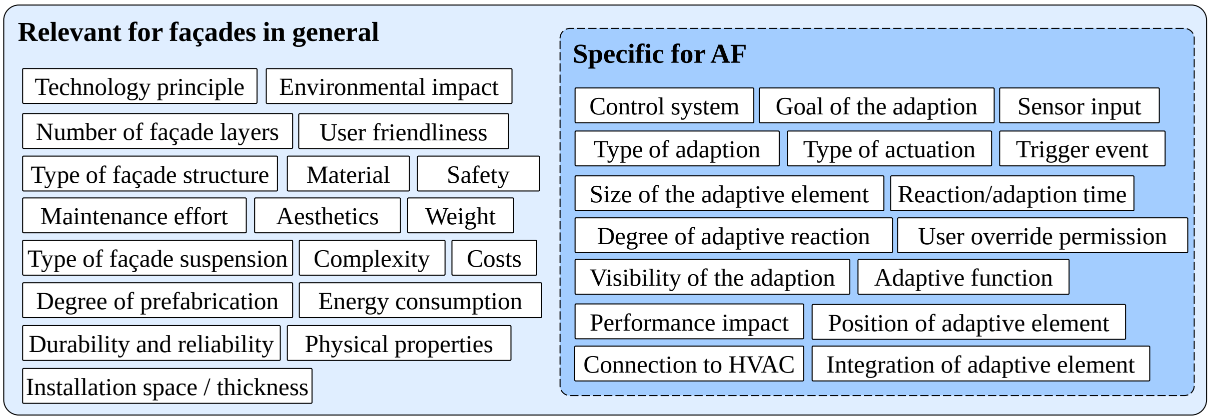

Figure 2. Differentiation between general and AF specific characteristics

In Figure 2, it can be seen that about half of the criteria identified apply specifically to AF. Table 2 provides brief descriptions of the AF-specific characteristics:

Table 2. Descriptions of the characteristics identified (1/2)

Characteristics:	Describes…
Control system	… what controls the AF (e.g. computer, intrinsic material properties).
Goal of the adaption	… the benefit of the adaption, compared to a conventional façade (e.g. increased thermal comfort).
Sensor input	… what the sensors of the AF system measure (e.g. photons of light, temperature changes).
Type of adaption	… how the adaption is realized (e.g. trough movement, change in shape or color).
Type of actuation	… the basic physical principle of actuation (e.g. pneumatic or magnetic actuation).
Trigger event	… the event on which the adaption takes place (e.g. wind loads or sun location).
Size of adaptive element	… qualitatively the spatial size of the adaptive building component (e.g. façade element, façade system or the whole envelope).
Reaction/adaption time	… the reaction time of adaption (e.g. seconds, hours or days).
Degree of adaptive reaction	… whether the adaption is adjustable gradually (e.g. on-off or gradual).
User override permission	… whether the user can override the pre-set control strategy based on their personal preferences.
Visibility of the adaption	… whether the adaption is visible (e.g. for the occupants or for passers-by).
Adaptive function	… the function of the façade that is realized to be adaptive (e.g. reject solar radiation).
Performance impact	… the impact of the adaption on the whole building performance.
Position of adaptive element	… the position of the adaptive element (e.g. outdoor, in between two façade layers, indoor, east, west, south…).
Connection to HVAC	… the connection to the HVAC (e.g. via air or water).
Integration of adaptive element	… how the adaptive element is integrated into the façade (e.g. replacing or additional).

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5. Support evaluation

The support evaluation according to Blessing and Chakrabarti (2009) checks whether the established support (in this case the identified criteria) in its initial form meets the requirements of *completeness*, *consistency* and *logic*. To check whether the requirements are met, a two-stage evaluation was carried out. First, experts were interviewed on the basis of which characteristics they would select adaptive (reference) façade systems in the early phase of the planning process. This was asked in order to determine the important characteristics of AF from the perspective of the practitioners. Secondly, to evaluate mainly the *consistency* and *logic* of the criteria, the identified characteristics and their descriptions in Figure 2 and Table 2 were presented to architects and engineers of three current case studies of AF. It was therefore possible to examine which of the identified characteristics and criteria have already been a focal point in the case studies, and which characteristics of the set presented above have been neglected in the projects so far. Even though no claim can be made with regard to *completeness* at this point, it will be provided in sufficient quality for further research in this study by the systematic literature review, the expert interview and the three case studies.

5.1. Interview with experts from the façade industry

The survey of the experts took place in the context of an interview. The detailed demographic profile of the participants who took part in this interview has already been published in Voigt et al. (2021). Twelve experts with partly more than 10 years of experience in AF and from different disciplines (Architecture, Façade Planning, Building Physics and Environmental Engineering) *were asked* (without knowledge of an existing set of characteristics) *which characteristics they would use to select an AF in the early phase*. The result of the survey is presented in Table 3, with AF-specific criteria highlighted in bold.

Table 3. Frequency of characteristics named by the experts from the façade industry

	Qualitative																								**Quantitative**									
Characteristics:	**Control system**	**Goal of the adaptation**	**Adaptive function**	**Type of adaptation**	**Type of actuation**	**Trigger event**	**Size of the adaptive element**	**Reaction/adaptation time**	Technology principle	**Degree of adaptive reaction**	**User override permission**	Material	**Visibility of the adaptation**	Durability and reliability	**Sensor input**	Aesthetics	Complexity	Type of façade structure	**Integration of adaptive element**	**Connection to HVAC**	Type of façade suspension	**Position of adaptive element**	Degree of prefabrication	**Performance impact**	Costs	Safety	Environmental impact	Energy consumption	Physical properties	Number of façade layers	Weight	Installation space / thickness	User friendliness	Maintenance effort
Frequency:		1										1		3		2	3		1						2	1	3	2		1	5		2	1

The results show that most of the quantitative characteristics named by the experts from practice are also valid for façades in general. This is despite the fact that most of the participants stated they already had experience with AF. Actually, only few AF-specific characteristics were identified by the experts. This could be confirmation for the need for such a comprehensive set of AF-specific criteria, since there may not yet be clarity about the specific characteristics.

5.2. Case studies

In addition to the interview, an initial practical test of the criteria was conducted on three current case studies of AF. The detailed description with pictures of the innovative case studies will be published in following papers of the Collaborative Research Center (CRC) 1244 in Stuttgart; a brief impression is given here. In the CRC 1244 the world's first adaptive high rise building with an actively controllable structure is developed (Blandini et al., 2022). The 36 m high building will be covered by different AF on each of the 12 floors. All three case studies are part of the project and were in the preliminary design phase as the evaluation took place:

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1. The first case study is planned as an adaptive opening system on the ground floor of the CRC 1244 high-rise building. The façade is formed of several layers of fabrics (with special texture for aesthetic reasons). When people interact with the façade, it responds in such a way that an entire side of the building opens up and the boundaries between the interior and exterior space disappear. The opening will be accomplished by sliding the fabrics to the sides, similar to a theatre curtain. A central requirement is to highlight the hi-tech structure in the inside by using a partly transparent fabric.
2. The second case study adapts to the position of the sun. The idea is to use a large number of solar sails to both shade the building and cool the surroundings by reflecting excessive sun radiation back into the sky. The structure of the façade will be done with tensegrity structures. This can be especially efficient in dense cities, as intense solar radiation heats them up as most of the area is sealed and cooling plants and green areas are missing.
3. The third case study uses solar energy to cool the interior. This is done by a 3-step process and with the help of the material Zeolith. Zeolith releases a high amount of heat when interacting with water. First, starting with wet Zeolith, the material is dried with the help of sunlight. The evaporated water will be condensed and stored on the cooler (north) side of the building. When the sun moves and the Zeolith cools down, the water is released into a chamber in the inside of the building to get evaporated with the help of the room temperature (on lower pressure). The steam will then be guided into the Zeolith again, which binds the water and releases the emerging heat back to the surrounding. (Schaefer et al., 2021)

To describe the evaluation procedure, first the responsible architects and engineers were asked to name the relevant characteristics of their AF designs. Subsequently, it was checked which of the criteria identified in the literature were additionally relevant for their project. The results are presented in Table 4. In this case, "+" means that the architect/engineer already named the characteristic in answer to the first question. Characteristics marked with "x" are criteria which, after going through the compiled set, were confirmed as relevant to the project. Although these criteria have already been discussed in the project, they were either not discussed in detail, or they were not a focal point for the participants, given that they were not named in the context of the first question. Characteristics that are marked with an "o" are open points that have been identified as relevant, but have been overlooked in the project up till now. Criteria marked with "-" are not relevant for the respective project.

Table 4. Results of the application of the identified characteristics in three AF projects

	Qualitative																								Quantitative									
Characteristics:	**Control system**	**Goal of the adaption**	**Adaptive function**	**Type of adaption**	**Type of actuation**	**Trigger event**	**Size of the adaptive element**	**Reaction/adaption time**	Technology principle	**Degree of adaptive reaction**	**User override permission**	Material	**Visibility of the adaption**	Durability and reliability	**Sensor input**	Aesthetics	Complexity	Type of façade structure	**Integration of adaptive element**	**Connection to HVAC**	Type of façade suspension	**Position of adaptive element**	Degree of prefabrication	**Performance impact**	Costs	Safety	Environmental impact	Energy consumption	Physical properties	Number of façade layers	Weight	Installation space / thickness	User friendliness	Maintenance effort
Case Study 1:	x	x	+	+	x	x	+	o	x	x	o	x	x	x	x	+	x	x	x	x	x	-	x	x	x	o	x	o	x	x	x	x	x	o
Case Study 2:	o	+	x	+	o	x	x	x	x	x	+	x	x	o	o	+	+	x	+	o	o	x	x	+	+	o	o	+	x	x	+	x	o	+
Case Study 3:	x	x	x	x	x	x	x	x	x	x	o	x	o	+	x	+	x	x	-	+	x	x	x	x	x	o	x	x	+	+	x	x	+	o

The *consistency* of the criteria was checked by how many of the characteristics were either named by the respondents themselves or confirmed as relevant. Only the criteria that were described as irrelevant for the project have a negative influence. This results in a very high consistency between the listed and verified criteria of 0.97 (33/34) for Case Study 1, 1.0 (34/34) for Case Study 2, and 0.97 (33/34) for

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Case Study 3 considering all identified characteristics, and 0.94 (15/16) for Case Study 1, 1.0 (16/16) for Case Study 2, and 0.94 (15/16) for Case Study 3 considering only the AF-specific characteristics. *Logic* was confirmed in the sense that the interviewees in the case studies understood both the criteria and the descriptions, which was a requirement for confirming the relevance in the respective projects. Furthermore, it was considered positive that the criteria were filtered to AF-specific criteria.

Regarding initial *completeness* of the criteria, it can be stated that only one characteristic mentioned in the expert interview and the case studies is not represented in the current set: the "surface of the façade". Since this characteristic is also relevant to non-adaptive façades, it is not included in the set of AF-specific characteristics.

The results show that the main characteristics found not only meet the requirements of the support evaluation, but also that the list of main characteristics can be a decisive assistance in the development. This is particularly demonstrated by the fact that only a small fraction of the criteria was identified by the stakeholders themselves in the interview and the case studies (+), but in return almost every criterion plays a role in the three case studies examined (+ and x).

6. Conclusion and further research

This paper has examined the main characteristics of AF to support understanding in the early project stages and decision-making when defining appropriate planning goals. A systematic literature review was conducted to identify the main characteristics of AF. Thirty-four characteristics were identified and divided into two groups based on whether they are AF-specific, or apply to façades in general. This resulted in 16 characteristics that are specific to AF. To counter-evaluate the results, a support evaluation was carried out. *Completeness*, *consistency* and *logic* were checked. The evaluation took place on two levels. Firstly, an interview with experts and secondly, the application of the criteria to three current case studies of AF. The evaluation showed very good results in each dimension, which makes the elaborated result suitable for further research and first application in practice.

Further work must analyze the range in which the parameters of the determined characteristics occur and which set of design parameter solutions can be derived for AF. This will be examined in part 2 of the research (see Figure 3).

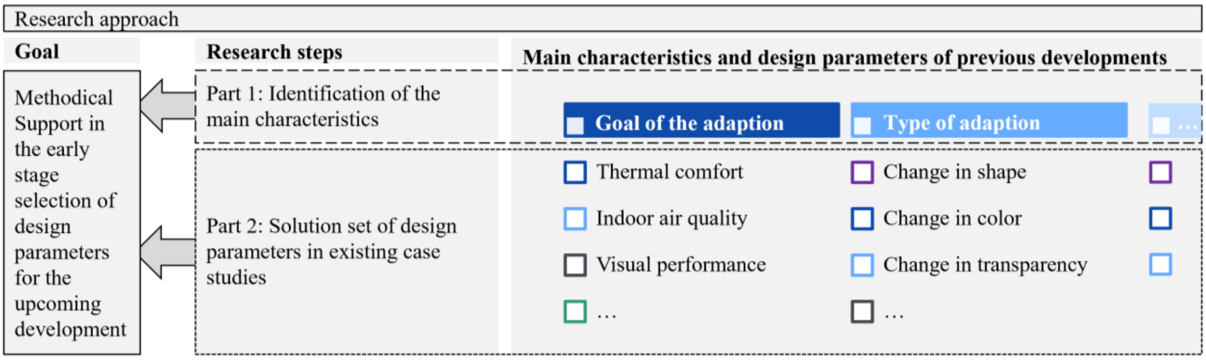

Figure 3. Visualization of the (further) research approach

Regarding the implication to practice, on the basis of the identified characteristics and the solution space of design parameters, a methodical support can be provided to help the interdisciplinary decision making in the early design phases. It would also be conceivable to classify corresponding AF examples on the basis of the characteristics and parameters and thus provide a database whose classification points are systematically elaborated. This can further improve understanding through the information provided and thus also reduce existing skepticism about the new technology of AF. As more and more digital and methodical support (e.g. BIM) is being used in the construction industry and in the field of AF, the criteria determined can also be used as a basis for the further development of existing tools and methods. The extension to include the main characteristics of AF would allow existing methodological support in the field of façade planning to quickly become practicable for AF as well. However, this hypothesis needs to be evaluated in further research.

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