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Decision Support for Defining Adaptive Façade Design Goals in the Early Design Phase

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Abstract: Compared to conventional façades, adaptive façades (AFs) can adjust their properties in response to environmental changes and user requirements. Often performed through the integration of actuators, sensors, and control units, this provides benefits such as reduced energy consumption in buildings but also increases the complexity of the façade design. To efficiently deal with the higher complexity, this article aims to provide suitable decision support for the early design phase, identify suitable design goals, and compare these to previously implemented Afs (make-or-buy decision). There is particular focus on the AF-specific characteristics, as these are new compared to well-known conventional façades. To systematically develop decision support, requirements are identified in expert interviews and the literature, and the current state of the art is evaluated against these. Research gaps found in current methods are addressed in this article, and continuous decision support is developed for the early design phase of an integrated design process. This support includes a checklist with AF-specific characteristics and a digitally implemented database of AFs. Based on the requirements, an evaluation is performed for both methods: this includes the comparison of the results to three ongoing AF projects and the assignment of 40 case studies to the database.

Keywords: decision support; adaptive façade; design process; methods; early design phase; comprehensive perspective

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1. Introduction and Research Objective

The main functional task of façades is to separate the inside from the outside and to protect the interior space from environmental influences such as precipitation, wind, or intense solar radiation [1]. However, conventional façades are usually designed statically and can only buffer the environmental influences to a certain extent. Any remaining comfort deficits due to changing environmental conditions are compensated for by the building's technical equipment (e.g., lighting, heating, or air conditioning), which accounts for approx. 70% of the total energy consumption of residential buildings [2].

In contrast, adaptive façades (AFs) are characterized by their ability to adapt automatically [3] to environmental changes through their adjustable properties [4]. This can be achieved, for example, through the integration of sensors, actuators, and a control unit, regulating the effect of environmental changes on the interior (e.g., the amount of solar radiation or air passing through the façade). On the one hand, this makes it possible to reduce the building service equipment (HVAC) necessary for ensuring indoor comfort and therefore reduce energy consumption [5]. On the other hand, the adaptability of the façade properties can positively affect the conditions in the surroundings of the building, for example, reducing overheating in cities [6]. The façade can therefore be adapted in many different ways, such as changing the amount of solar radiation passing through the façade [7], adjusting the ventilation [8], or cooling the surroundings with evaporating water [6].

The downside of these types of façades is their higher complexity, which produces additional challenges over the entire lifecycle of the AFs [9]. These challenges have been systematically elaborated and can be assigned to two main issues [9]. The first issue is the higher technical complexity of the AF system itself, which, for example, complicates the design and early definition of suitable design goals [10]. This leads to the need for an interdisciplinary team to deal with the different aspects of an AF [4]. However, raising the number of stakeholders participating in the design results in the second issue of increased procedural complexity, as this team needs to be organized and managed. To compensate for this, corresponding design and procedural support are needed [9]. As it is known that the decisions in the early phases have a significant influence on the overall development and the performance of the final product [11], this article will focus on the earliest design phase of the AF design process.

For this purpose, the first design phase (basic evaluation phase) of the integrated design framework developed by Voigt et al. [12] is used as a reference. This framework considers all lifecycle phases of an AF as well as the stakeholders that are involved in them. Figure 1 shows an excerpt of the framework, highlighting the basic evaluation phase with subsequent steps.

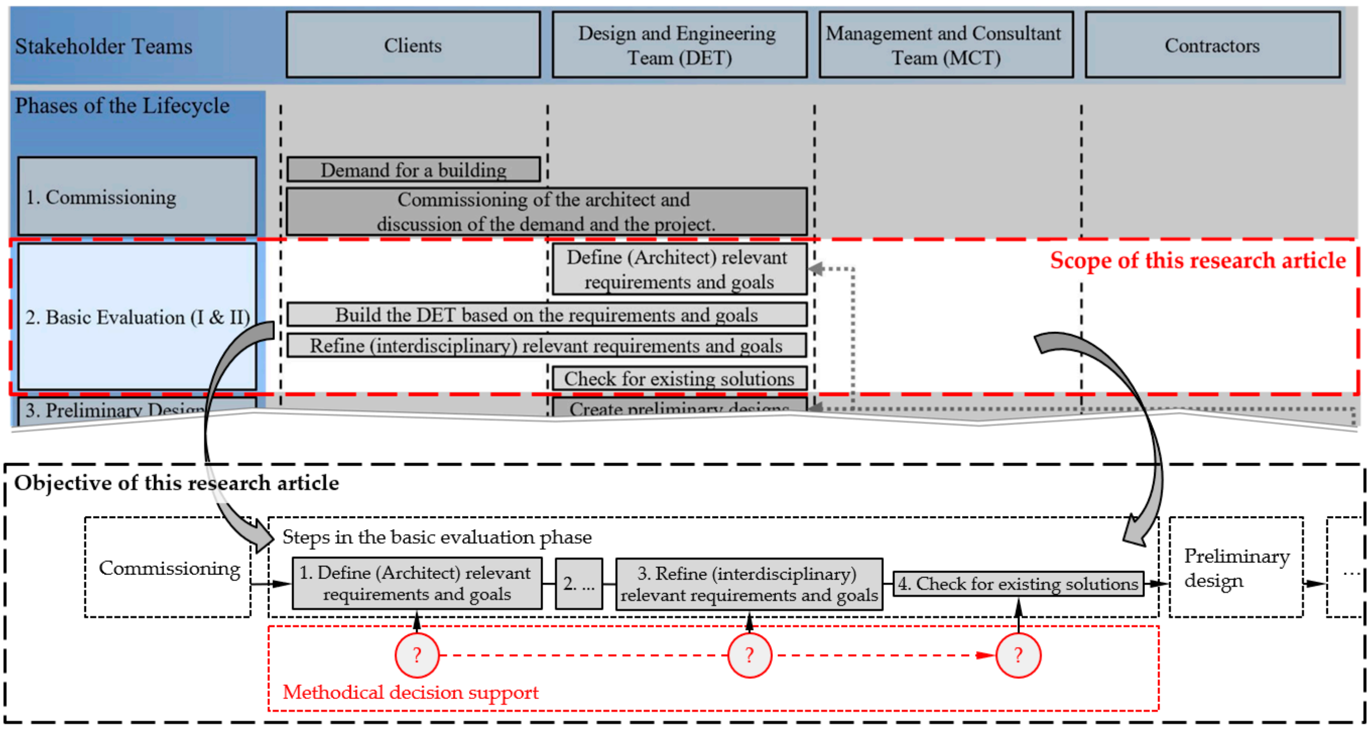

Figure 1. Excerpt of the early lifecycle phases of the integrated design framework by Voigt et al. [12], scope, and objective of this article—question marks indicate the search for suitable methodical support.

Further, the lower part of Figure 1 shows the objective of this research article and picks out the steps of the basic evaluation phase that deal with **decisions related to design goals.** Here, three question marks indicate the search for suitable decision support in the related steps.

The three steps can be described as follows:

1. The definition of (rough) requirements and design goals (as the first step after the commissioning of an architect by the client) performed by the architect in the form of drawings, descriptions, or initial models.
3. The interdisciplinary re-definition of these design goals with more diverse discipline-specific knowledge of an interdisciplinary team.
4. The search for adaptive reference façades that might already meet the selected objectives. This step involves deciding whether a new AF has to be developed or whether

an existing solution can be used or modified (make-or-buy decision), and accordingly has a very high influence on the subsequent steps of the design process, the design goals, and possible partners/stakeholders.

The second step, dealing with the definition of the Design and Engineering Team is not considered in this article, as the decisions there highly vary between the projects and are characterized by personal and situational constraints that are partly independent of the AF-design-related scope here. However, first approaches to support the team selection are presented, for example, in [13].

Reviewing the current literature on decision support linked to early AF design process phases, the scope of this article deepens once more as the following crucial points stand out:

- Most of the process descriptions that consider the early phases start with identifying requirements and design goals [10,14–19] but rarely present suitable support for defining them.
- Existing decision support for defining design goals and requirements in the design process [18–20] varies significantly with regard to the research focus and the AF characteristics that are seen as relevant.
- Widening the scope, existing classification approaches of AFs [3,19,21,22] that could be used to support the definition of AF design goals are inconsistent and highly variable. This suggests that the understanding of AF systems is currently incomplete, which complicates decision-making in the early design phases.

Therefore, the objective of this article is *to derive consistent methodical support for the definition of suitable design goals and decision making in the basic evaluation phase of an integrated design process* (see Figure 1). The objective can be further divided into two main steps. First, the aim is to gain a better understanding of AF technologies, and second, methodical support is derived. The more detailed procedure is presented in the next section. Hereby, this research article presents original research based on the synthesis and refinement of several preliminary investigations that has been published partially in two conferences. This body of knowledge has been expanded with regard to new findings and revised with a focus on the development of a consistent methodology that is presented in this paper.

2. Methodology and Research Questions

In this section, the research methodology, the structure of this article, and the corresponding research questions are presented (see Figure 2).

Based on the research needs identified in the introduction, this article systematically develops methodological decision support for the basic evaluation phase of the integrated design process of AFs. In Section 3, the search for reference applications leads to the identification of checklists and solution collections as being suitable for the design task. Therefore, the first step is to identify the requirements that need to be met by the methods. Section 3 thus answers the research question "*What are the requirements for a suitable checklist and corresponding solution collection to serve decision-support in the basic evaluation phase?*" Each of the following sections includes investigations for the checklist and the solution collection. For both methods, a literature review in Section 3 forms the basis for the definition of suitable requirements.

As the development of the solution collection is more complex than the development of the checklist, expert interviews were also conducted to better understand the research task and include a practical perspective. Interviews were conducted with ten experts from different disciplines (architecture (4 experts), system dynamics (2), computational architectural design (1), civil engineering (1), lifecycle engineering (1), and building physics (1)); these individuals boasted a combined 23 years of experience in the field of AF development, and each had at least 1.5 years of experience.

After introducing the experts to the research task and the scenario presented in Figure 1, the following questions were asked:

1. Would you consider the scenario presented here, which describes the search for adaptive reference façades, to be correct?
2. What methodical support can you imagine being useful in this scenario?
3. Which requirements would you raise for such methodical support?

The experts agreed that the scenario is correct and called for a solution collection if methodical support is developed for it, as it greatly reduces the research effort. Furthermore, they agreed that it helps to get an overview and a better understanding of the current technologies on the market, as well as to provide inspiration for their own project if no suitable AF systems were found. All requirements subsequently identified for the solution collection were included in the requirements list in Section 3.2.

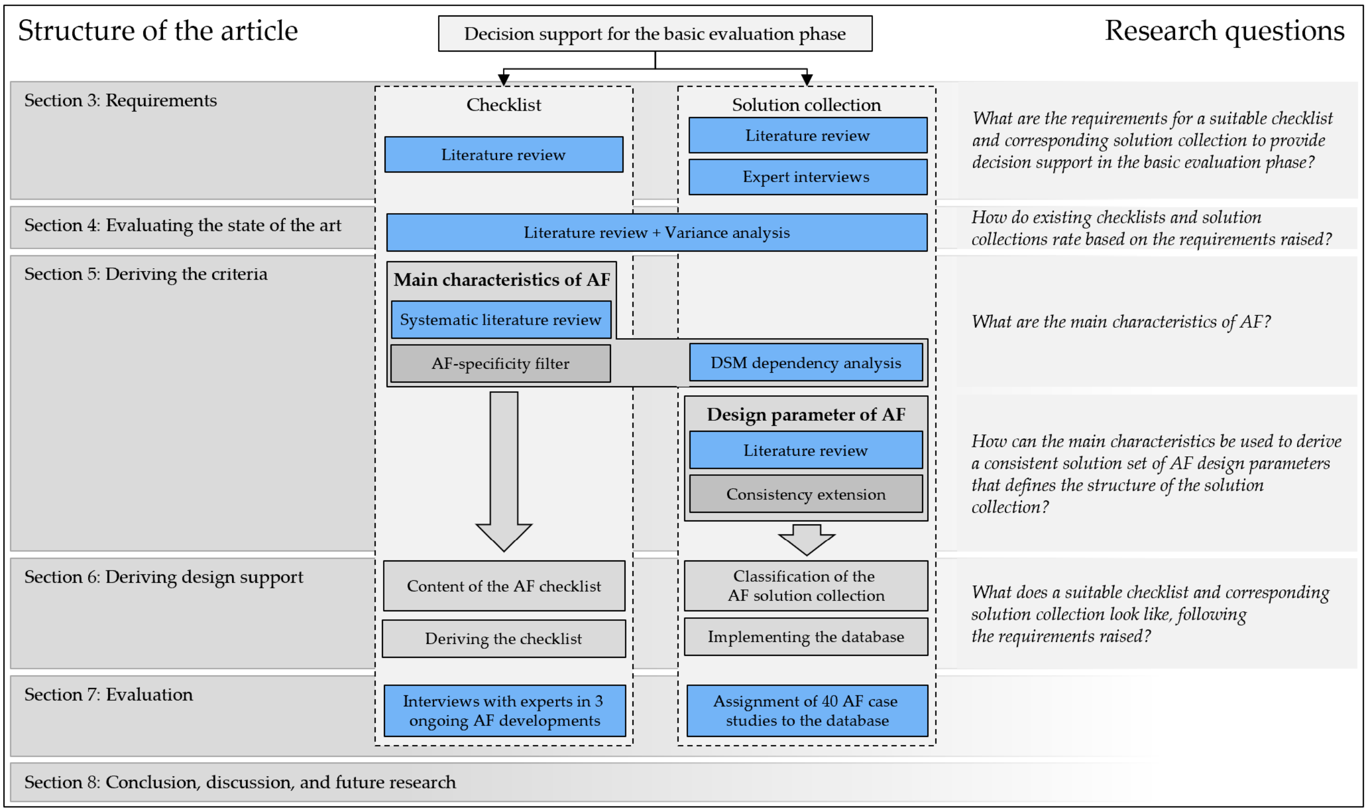

Figure 2. Structure of the article, research questions, and methodology—methods used are highlighted in blue.

Based on the requirements, an evaluation (variance analysis) of the current state of the art for checklists and solution collections is conducted in Section 4. Here, the research need is also specified, as several current research gaps are revealed. The question to be answered is "*How do existing checklists and solution collections rate against the requirements raised?*" To identify existing checklists and solution collections in the literature, a literature search was conducted in November 2022. Three search engines were used to find scientific solution collections (Web of Science, Wiley) and potentially also commonly used or commercial solution collections (the first 100 Google results were reviewed). The search included synonyms for adaptive (kinetic, movable, smart), façade (envelope, building shell), and checklist (criteria list) or solution collection (atlas, catalog, database).

After the research need is specified, a consistent set of main characteristics and design parameters of AFs is developed in Section 5. The corresponding research questions to be answered are "*What are the main characteristics of AF?*" and "*How can the main characteristics be used to derive a consistent solution set of AF design parameters that defines the structure of the solution collection?*".

As can already be seen in the research questions, both methods strongly rely on the criteria (main characteristics/design parameters). Therefore, a significant effort was made to obtain a comprehensive and consistent set of criteria. For this purpose, the research refers back to a systematic literature review conducted and published in a previous conference study by Voigt et al. [23], which was intended as a preparation for this article.

The review involves the following four steps:

1. Identifying suitable synonyms for the terms "classification", "adaptive", and "façade", in English and German, using wildcards ("*") wherever useful.
2. Performing a literature analysis based on the synonyms in four electronic databases.
3. Multistage filtering of the results according to Figure 3.
4. Detailed review of the remaining papers.

Based on the terms found in the first step, the main literature analysis was performed in March 2021 using the following electronic databases: Science Direct, Web of Science, Pro Quest, and Wiley Online Library. Due to the high degree of evaluated consistency and initial completeness in this pre-study, the determined set of criteria is still considered up-to-date.

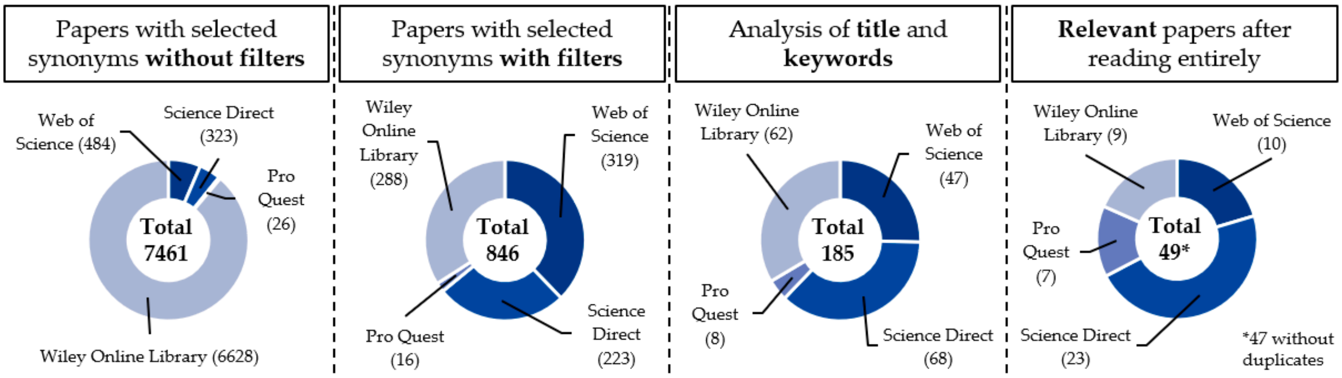

Figure 3. Results of the systematic literature review adapted from [23].

The initial search using only the identified synonyms found 7461 results (see Figure 3, left). After applying filters such as the subject area (the available filters vary between the different search platforms but were selected according to relevant fields for AFs such as architecture, environmental engineering, material science, building engineering, construction, mechanical engineering, and automation control systems), the results dropped to 846. Further analysis of the title and keywords resulted in 185 papers of special interest, of which 47 were identified as relevant to the first research question after reading the articles completely (see Figure 3, right, without duplicates). The result of the literature review is presented in Section 5.2.

Building on this, to answer the second research question in this section, the design parameters that AFs have previously represented within each of the main characteristics are listed and a consistent set of criteria is derived. To ensure the quality of this set, this article again refers to a conference pre-study [24]. Here, a systematic development of the design parameters was carried out based on the main characteristics. The central aspect of this is a DSM dependency analysis that shows the dependencies of the design parameters and a clustering process to group dependent characteristics. Based on the dependencies, the set of design parameters from the literature can be extended, and a consistent and more complete set of design parameters can be derived. The final set is presented in Section 5.4.

Building on the set of main characteristics and design parameters, the actual methodical support is derived in Section 6. The research question here is "*What does a suitable checklist and corresponding solution collection look like, following the requirements raised?*".

After the methodical support is developed, a comprehensive support evaluation is carried out in Section 7. Here, for both methods, an evaluation of the identified criteria is conducted first, and then the methodical support is evaluated against the requirements—similarly to the evaluation of the state of the art. This includes interviews with experts of three different AF case studies for the checklist and the analysis of forty already-built case studies for the solution collection. Section 8 concludes the study, discusses the research, and gives insights into possible future research.

This article is part of a larger multidisciplinary research project on the refinement of design support for the development of AFs and contributes to a "comprehensive descriptive study one" and a "prescriptive study" according to the Design Research Methodology (DRM) presented by Blessing and Chakrabarti [25]. The DRM presents one of the most established ways to systematically develop methodological support in product development.

3. Identifying Requirements for Methodical Decision Support in the Basic Evaluation Phase

Analyzing the three design steps described in the introduction, it is noticeable that the first and third steps include very similar tasks. The approach is that the definition of early design goals can be supported by a list of main characteristics that describe the different aspects of AFs comprehensively. Similar tasks of defining design goals are, for example, already supported by checklists in the field of engineering design [26,27] (illustrated in Figure 4). For the fourth step, in contrast, a different task has to be accomplished. Selecting or checking for reference solutions often requires a lot of research and is therefore time-consuming. In this context, the interview with the experts revealed solution collections to be useful as all (or at least many) of the possible solutions can be quickly found in one place. As the scope of this research lies in the basic evaluation phase of an integrated design process, the search for existing solutions in this step will mainly use qualitative criteria [28] based on the design goals and requirements derived in the previous steps. As quantitative comparisons are most likely only possible in later design steps [29], it is suitable to build the solution collection based on the qualitative main characteristics of AFs.

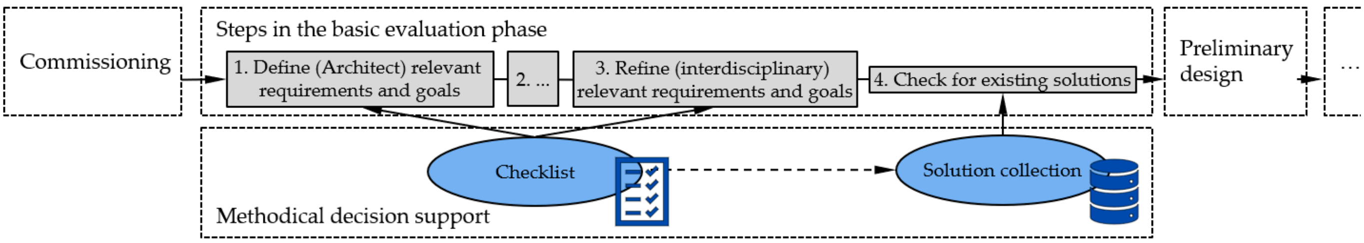

Figure 4. Deriving decision support for the basic evaluation phase of AF design.

Because both intended methods are discursive methods, according to the theory of engineering design methodologies, they require preparation and prior elaboration of the specific content [26]. Furthermore, as both methods are intended to be based on the same characteristics, consistent decision support for the basic evaluation phase can be ensured. Here, the AF-specific design goals that are selected in the first steps will also be found in the solution collection later.

The development of methodological support first involves the identification of requirements. The following two subsections introduce the methods and the associated requirements.

3.1. Requirements for the Checklist

Checklists are simple but effective methods for providing information and supporting both decision-making and the definition of requirements/design goals [26,27,30] in the early phases of the design process. Due to their simplicity, checklists mainly depend on their content—in this case the criteria. The checklist is therefore subject to these requirements:

(1) The content should be (initially) completed [25,27,31];
(2) The descriptions need to be comprehensible [25,27,31];
(3) The descriptions/criteria need to be objective and consistent/logical [25,27,31];
(4) The criteria need to be specific to the product or product type of interest [27].

3.2. Requirements for the Solution Collection

The second method to be developed is a solution collection of AF systems that is used in the basic evaluation phase. As solution collections exist in different variations (e.g., catalogs, databases, lists, etc.), and are more complex than checklists, an expert interview is conducted alongside a literature review to identify relevant requirements. The requirements listed in Table 1 are separated into formal requirements that emerge from a general methodological perspective, content-related requirements, and requirements regarding the visualization of the solution collection.

Table 1. Requirements for the solution collection of adaptive façades.

I	**Methodical Requirements**
1	The solution collection needs to be expandable to ensure it can be updated over time [21,32,33].
2	It should be possible to quickly identify the helpful content/aspects of the gathered data and the rules on which the structure of the method is built [28,33].
II	**Content Requirements**
1	The context needs to be company independent [28], although specific examples can refer to their manufacturer or architect [Expert Interview].
2	Product-specific (in this case AF) characteristics are to be used as classification criteria [33] that ideally describe the product well.
3	The classification and the corresponding criteria need to be consistent (free of contradictions) [33].
4	Criteria that classify and describe the content need to be independent of each other or the dependency must be described [28].
5	The content (A) and the classification approach (B) should be initially completed [28,33].
6	In addition to characteristics that describe the adaptive façade system itself, further constraints such as the location of the building are of interest [Expert Interview].
III	**Visualization Requirements**
1	Usability—the solution set should be convenient to handle [33]; in case of large datasets, this suggests a digital solution [34], e.g., with search and filter functionalities.
2	The solution collection should be built specifically for the use of architects and engineers in the basic evaluation phase. Therefore, the solution collection needs to consider aesthetic aspects (e.g., using pictures) as well as technical aspects of the AF systems [32].
3	The solution collection should be openly accessible [Expert Interview].
4	There should be a function for easily comparing several selected AFs with each other based on their characteristics [Expert Interview].
5	It should be considered that some of the stakeholders in the basic evaluation phase lack technical expertise [32]. As AFs are more technical than conventional façades, supporting descriptions explaining the necessary basics should be available [Expert Interview].

4. Evaluating the Current State of the Art and Defining Research Gaps

Based on the requirements identified for both methods, the state of the art can be analyzed and evaluated. For this, the authors compared the existing solutions found with the requirements and evaluated the existing solutions accordingly. This reveals gaps and also shows advantages that can be combined if useful.

4.1. State of the Art for Checklists in the Early Phase Decision-Making

In the current literature, checklists of main characteristics already exist to support early phase decision-making and the selection of appropriate design goals. One example is the (check)list for products [30] that is widely used in mechanical engineering. In the area of architecture, Schill-Fendl [35] describes checklists to be a valuable method for quality control during the architectural design process. Focusing on buildings with adaptive structures, Honold et al. [36] developed a list of main characteristics as well. In the area of façade design, Herzog and Krippner [1] present a perspective on the characteristics of conventional façades. For the area of AF in particular, Heiselberg [20,37] presents a checklist approach that aims to support the designer in identifying the most important issues of responsive buildings (including AF approaches). Although this list was not specially defined as a checklist, the intended use is similar. Finally, Basarir and Altun [38] define an AF checklist for the redesign procedure of AFs with standard products.

However, when comparing the approaches of AF checklists with the requirements raised in Section 3.1, several gaps become apparent. First, the characteristics used to describe AFs are not complete in terms of the broader perspective taken in this research (Requirement 1), as the criteria used in existing checklists to describe the main characteristics of AFs are different to those used, e.g., in classification approaches. Several of the characteristics stated (e.g., climate, context, building use, building type, etc. [20]) are relevant for any type of façade or building and therefore not specific to AFs (Requirement 4). This raises the need to identify a more complete and specific set of main characteristics to be used in the checklist in the basic evaluation phase. This specific list can then be used as an extension of the perspective on conventional façades [1] or products [30]. In addition, this research takes the approach that for clients, façade planners, and architects who are working with AFs for the first time, the AF-specific characteristics in particular cause uncertainty and skepticism, thereby inhibiting the application of the technology on a larger scale [9,39].

4.2. Evaluating the Current State of the Art on Solution Collections against the Requirements Raised

Building on the requirements identified in the previous section, an evaluation of the existing solution collections is now conducted. Here, a large number of collections exist in the literature, but most of them are highly specialized in single aspects of AFs and their variety of solutions or working principles is therefore quite small. To give some examples, Heusler [40] presents nine different movement typologies of AFs. Zhang et al. [41] present fourteen active solar thermal façade systems. Yoon [42] shows five different types of smart materials for AFs and orders them based on six different characteristics, while Luna-Navarro et al. [43] focus on the human-AF interface and present their observations in thirteen different scenarios. All of these provide a useful overview of their topic but are not aiming to generate a broader understanding of AFs. In general, multi-criteria investigations covering different areas of AFs are rare in this context [44]. To investigate the solution collections in particular with a comparable broader objective, a minimum limit of AF solutions is introduced. In the following, only solution collections with at least 20 AF solutions are evaluated. Furthermore, the number of criteria in the classification approach (column 5B in Figure 5) also includes non-AF-specific characteristics. The evaluation is shown in Figure 5, with the references and their main focus being shown in the first two columns. These are followed by the evaluation according to the requirements. The requirement numbers are the same as in Table 1 and are briefly described in the lower part of the table.

It can be seen that the identified solution collections perform quite well in terms of the requirements raised in the previous section. Nevertheless, there are some gaps. First, most of the solution collections are developed on paper, which reduces the likeliness of being scalable or updated over time (I-1). As the (inter)dependency between the classification criteria is not elaborated (II-4), this might bias the selection decision of the user.

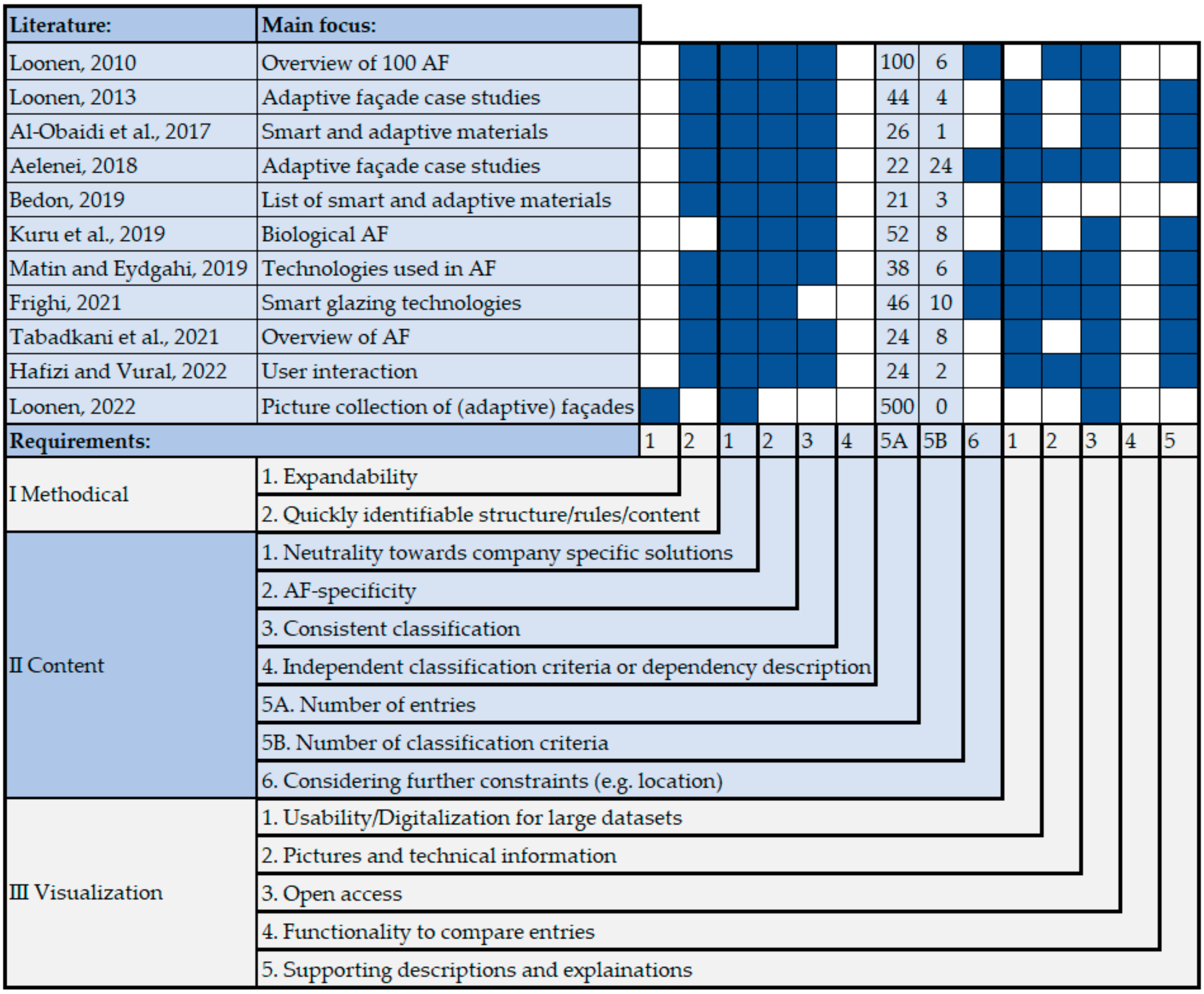

Figure 5. Evaluation of the existing adaptive façade solution collections [22,45–54] and identification of research gaps.

Only half of the reviewed solution collections provide further information about the location or orientation of the AF (II-6). Additionally, considering the visualization, a solution collection often focuses either on pictures or technical information (III-2), and none of the solution collections provide the functionality of easily comparing several selected AFs with regard to their descriptions (III-4). Although this is not possible with solution collections in tabular form on paper (and not necessary with a small number of entries), the comparability exponentially worsens with the number of entries, which makes the functionality of easily comparing entries (and therefore digitalization) especially necessary for larger-scale collections. It can also be seen that the more comprehensive collections most often focus on either the classification criteria [21,47] or the entries [44,52]. However, taking a closer look at the two solution collections with many entries, it becomes clear that only the solution collection by Loonen [44] deals solely with AFs. In the solution collection on Pinterest [52], around half of the façades are not seen as adaptive according to the definition of automatization in Section 1. The other solution collections [21,45,46,48–51] present a more balanced ratio of classification criteria and case studies. None of the solution collections that are evaluated against the requirements can fulfill all of the requirements, which shows the need for further research. Nevertheless, the advantages can be referred to and combined for the purpose of developing a suitable solution collection.

5. Deriving a Consistent Set of Main Characteristics and Design Parameters

As the analysis of the state of the art revealed the need for further research, a consistent set of criteria is developed below. On the one hand, this includes the set of main characteristics that is needed for the checklist (referring to the preparation work in [23]), and on the other hand, this includes the set of design parameters (referring to the preparation work in [24]) within each of the main characteristics (see Figure 6). The main characteristics and the design parameters together will form the structure and classification of the solution collection.

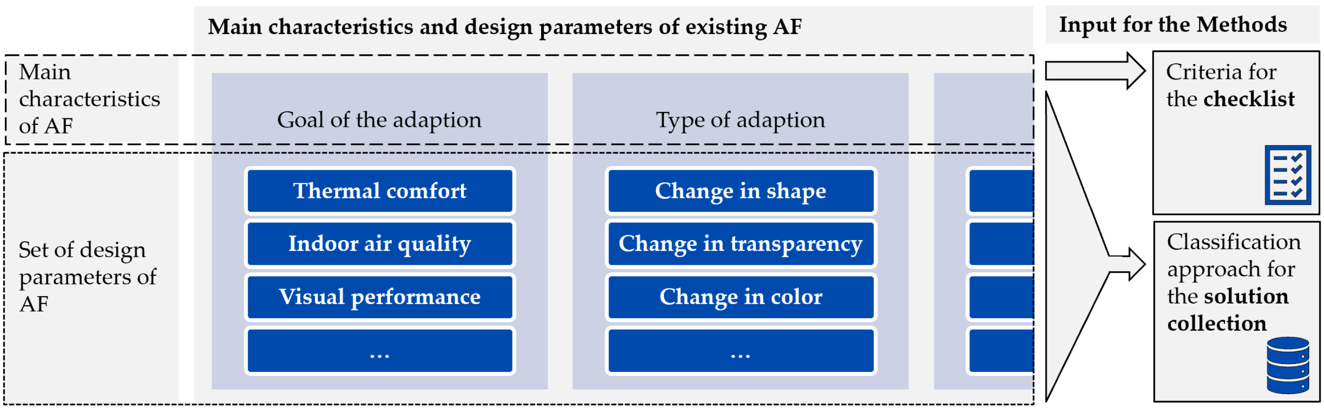

Figure 6. Relationships between the sets of main characteristics and design parameters and the methods to be developed.

5.1. *Characteristics That Are Used to Describe Adaptive Façades in the State of the Art*

The pertinent literature includes a range of existing classifications and sets of solutions for AFs. Although there is often information according to the associated architect or location [50], these aspects are not product-related parameters but rather boundary conditions for an AF system and therefore not focused on the set of product-related characteristics. A systematic literature review is conducted according to the descriptions in Section 2. Figure 7 presents the analysis of the 47 relevant papers. The product-related characteristics are listed horizontally, whereas the literature references are listed vertically. The results are reworked and refined, providing a more consistent version in the context of the method development of this article than was the case for the draft in [23].

As can be seen in Figure 7, the marked cells represent the characteristics that were found in the literature. The identified characteristics are further separated by qualitative and quantitative criteria according to their descriptions in the literature. In the last line, the frequency with which the criteria are mentioned is shown. The characteristics are further listed in descending order from left to right, depending on their frequency.

Figure 7 shows that the different classification approaches vary highly between the different literature sources, including the list of characteristics by Heiselberg et al. [37]. Yet although the literature review was carried out systematically, the degree of completeness of this collection must be subject to further evaluation. This is carried out in the evaluation part of this article.

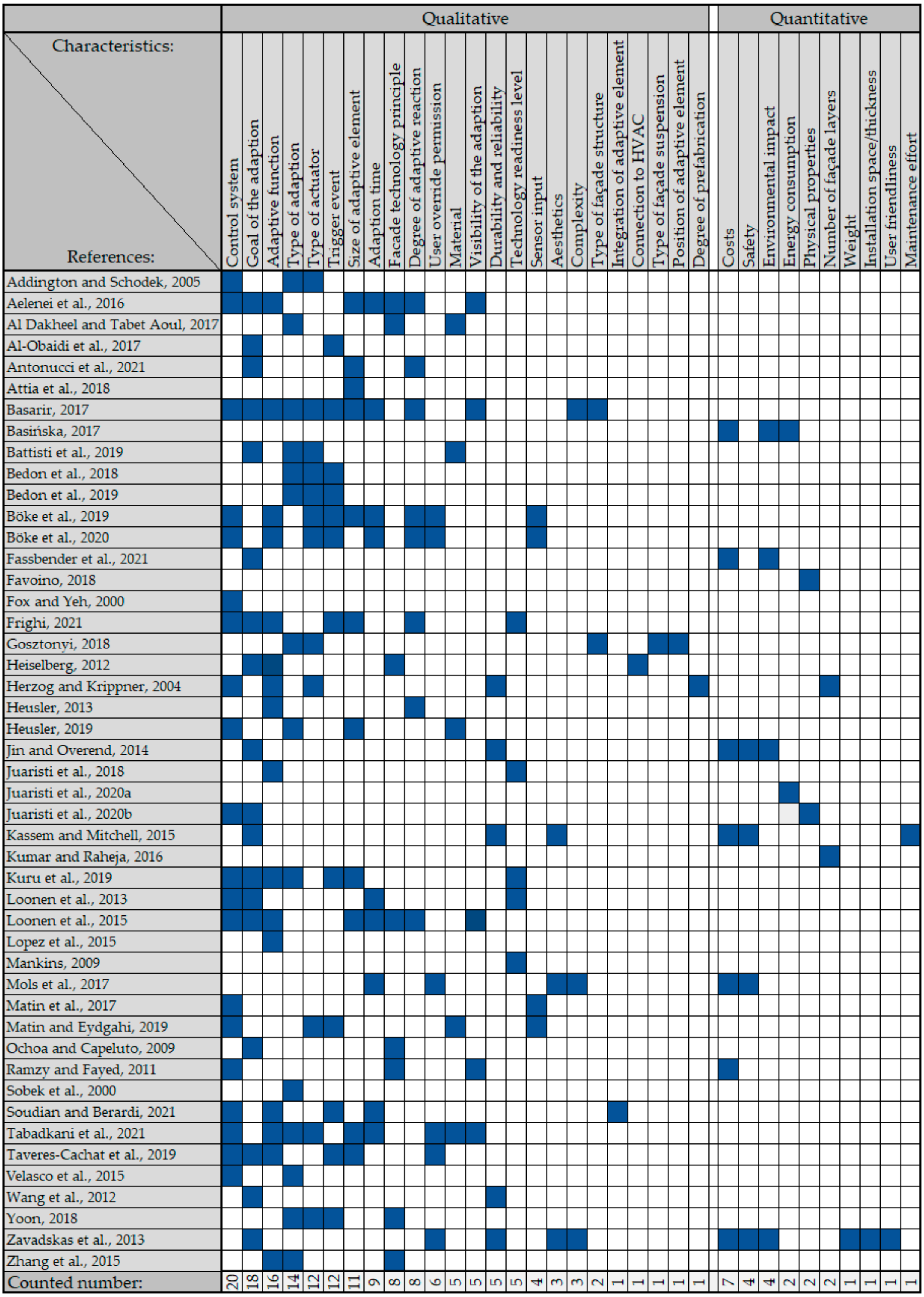

Figure 7. Comprehensive set of main characteristics of adaptive façades [1,3,4,18,19,21,22,37,41,42,46,47,49–51,54–85], refined from [23].

5.2. Set of Main Characteristics of Adaptive Façades

Although the analysis in the previous subsection only considered the literature dealing with AFs, it is noticeable that some of the characteristics are valid for any type of façade or even general products (e.g., costs, weight, material). As the analysis of the state of the art revealed, checklists already exist for products and façades in general. The focus here is on the characteristics that are specific to AFs. In this way, the checklist will supplement the existing checklists and can be used for the design of AFs in particular. A filter process is performed accordingly to obtain a more specific set of main characteristics, thereby distinguishing between the criteria that are specific to AFs and those that are valid for façades or products in general. As can be seen in Figure 8, about half of the criteria identified are specific to AFs. Section 5.4 provides a detailed description of each of the specific main characteristics together with the subsequently assigned design parameters.

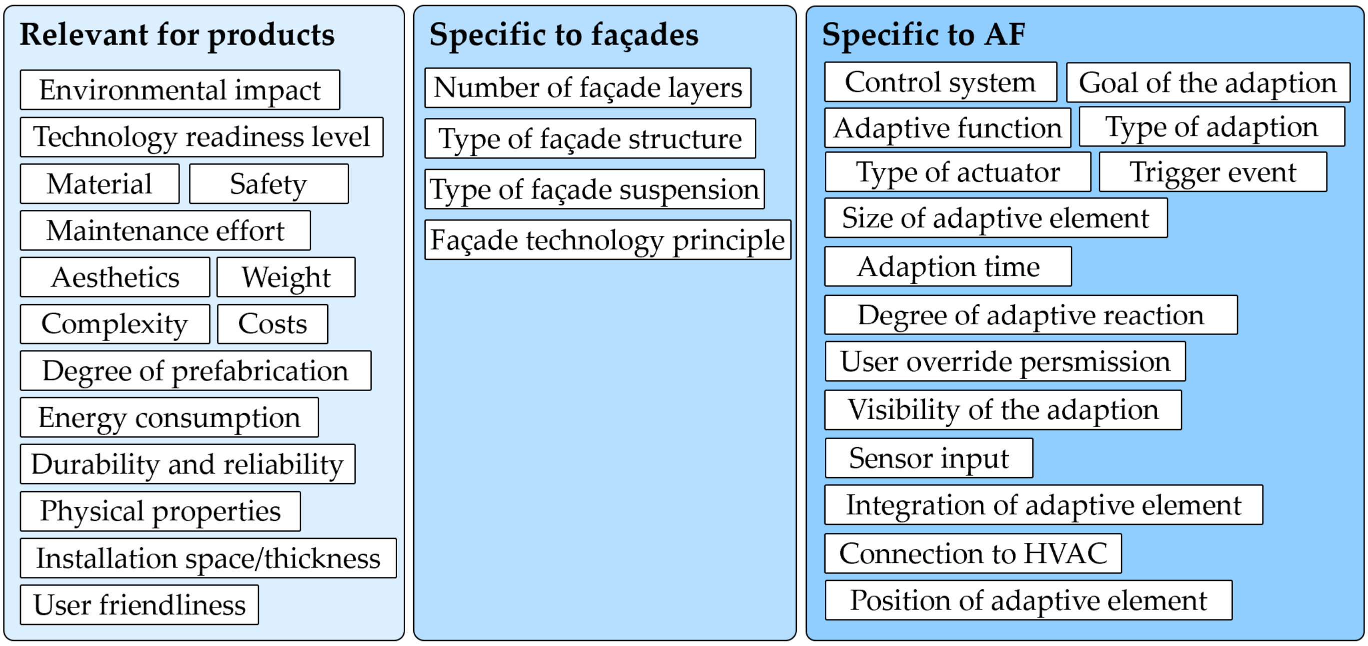

Figure 8. Differentiation between characteristics relevant for products in general, characteristics relevant for conventional façades, and AF-specific characteristics.

5.3. Preparing the Set of Design Parameters Based on the Main Characteristics

Based on the objective of developing a solution collection based on the same characteristics that were used for the checklist, further detailing and processing of the characteristics are necessary. The dependencies of the main characteristics are analyzed first, after which the design parameters are unified to form a consistent set of parameters.

5.3.1. Analyzing the Dependencies between the Main Characteristics

The dependencies of the main characteristics are analyzed according to the requirements raised in Section 3.2. This reveals the correlations between the criteria and simplifies the check for contradictions and consistency. The dependencies can be identified by comparing the descriptions of the design parameters that are already assigned to the main characteristics in the literature. To give an example, there is a dependency between the "sensor input" and the "goal of the adaption", as the goal of improving thermal comfort in the interior of the building requires temperature sensors. Analyzing the main characteristics in a similar way to this example, the dependencies can be identified and are presented in Figure 9 (left). Applying an optimization algorithm from Pimmler and Eppinger [86], the criteria can be reordered into clusters to improve the understanding of the dependencies of the criteria (see Figure 9, right). Two clusters in particular stand out. The first consists of "goal of adaption", "sensor input", "trigger event", and "adaptive function", and the second consists of "visibility of the adaption", "position of the adaptive layer", and "integration of adaptive element". In contrast to the clusters, the three characteristics show no direct dependencies.

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	Adaptive function		1				1						1			
4	Type of adaption		1									1				
5	Type of actuator								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	Sensor input		1	1			1									
13	Integration of adaptive element											1				1
14	Connection to HVAC															
15	Position of the adaptive element											1		1		

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

Figure 9. Deriving the dependencies between the main characteristics, adapted from [24].

5.3.2. Preparing and Unifying the Design Parameters

Based on the dependency analysis, a consistent set of design parameters can be developed. For this purpose, the existing descriptions in the literature are analyzed and the results of the 47 papers from the systematic literature review are combined. Afterward, the set can be extended (see Figure 10). The extension is possible 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** (result of the dependency analysis). Therefore, if there are no related parameters under the **main characteristic B** for the design parameters under the **main characteristic A** (e.g., *Ay*) in the descriptions from the literature, this requires a search to uncover these dependencies and identify *design parameter Bx* (or even several such design parameters) to include them in the existing collection.

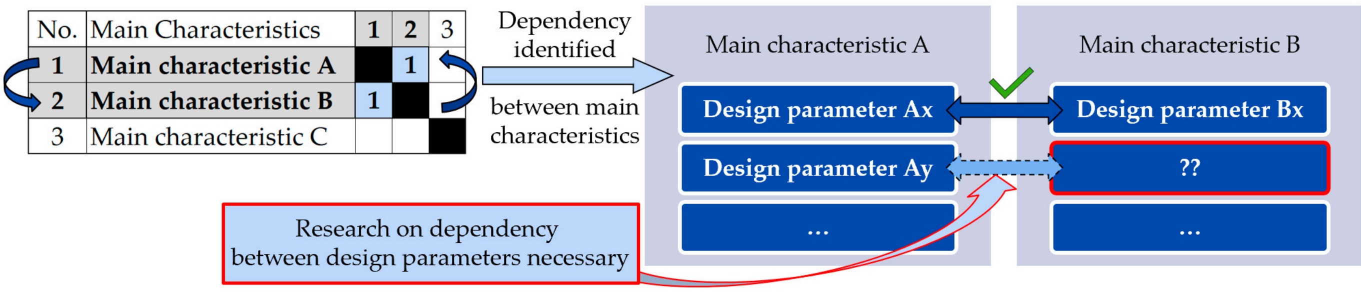

Figure 10. Extension of the identified design parameters due to consistency, adapted from [24].

One example for explaining the extension due to consistency is provided by *thermal comfort* (**goal of the adaption**). First, data are analyzed to identify which flows of material, energy, and/or signals/information can be adjusted to address the *thermal comfort* (*design parameter Ax*) in buildings. According to DIN EN ISO 7730 [87], the parameters that influence thermal comfort are (1) heat radiation from the floor and walls, (2) the speed of the air, and (3) the temperature of the air inside the room. When this information is related to the façade, the following parameters are relevant: *heat flux through the façade, ventilation or openings enabling airflow, and solar radiation through the façade* (*design parameters Bx*). In other words, it is about changing the conductivity of the façade with regard to heat flux, air, and solar radiation/light. This insight can then be compared to the descriptions of AF functions in the literature and the solution set of design parameters can subsequently be expanded. The other main characteristics and design parameters are processed in a similar manner.

5.4. Solution Set of Main Characteristics and Design Parameters in Existing Case Studies

Based on the preparation process of the design parameters, including the dependency analysis, the following design parameters can be derived (see Table 2). The majority of the design parameters could be identified by the analysis of the identified literature, but some of the criteria were added for the reason of consistency according to the explanations in the previous section. These added criteria are underlined. To ensure comprehensibility, the main characteristics and design parameters are briefly described here. The **control system** describes the way the façade is controlled. In this context, it is possible to distinguish between façade systems in which control is enabled by a separate control system with sensors and actuators that need additional energy to run (*extrinsic*) and a self-adapting behavior programmed into the material of the façade (*intrinsic*) which most likely does not require additional energy [21].

The **user override permission** describes the ability of the user to redefine the control strategy based on his/her personal preferences. This of course is highly affected by the control system, as intrinsic control is most likely immutably programmed into the material [76,81]. The **goal of the adaption** describes the intended benefit of adapting the properties of the façade. Different aspects are addressed in this regard. First, improved comfort such as *thermal comfort*, *indoor air quality*, *visual comfort*, or *acoustic quality* [21,49] can be assigned. In this case, visual comfort includes lighting but also visibility through the façade and therefore privacy. Further, e*nergy generation*, *interaction with humans* [21], as well as *aesthetics*, *lightweight design*, or increased *protective* properties (earthquake, fire, etc.), can motivate to design a façade adaptable. To narrow it down, only improvements primarily achieved by the adaptability of the façade are considered here. Positive secondary effects such as reduced environmental impacts due to resource efficiency in construction [88] are not considered here.

Depending on the goal identified for the façade's adaptability, different **adaptive functions** are realized by the façade. These can be specified by several operations (*change*, *conduct, store,* etc. [24]) that are executed on flows of *energy* [24] (e.g., *heat flux* [3,19,63], *sound* [63], *solar radiation/light* [3,19,63], *mechanical loads* [68], *wind* [63], *or fire* [68]*), material* [24] *(water* [50], *air* [63], *occupants/users* [42,81], *objects* [59], *etc.),* or *signals/information* [24] (*occupant/user* [42,81], *vision* [3], *sound* [63], etc.). The description of the AF functions here is based on the logic of Pahl and Beitz [26] and is new compared to the state of the art. A detailed derivation is presented in [24]. Sensors are necessary for realizing these adaptive functions in the case of extrinsic systems. Possible **sensor inputs** could be *lighting* inside or outside of the building [50], *temperature* [50], *moisture* [77], *magnetic fields* [50], *electricity* [50], *wind* [3], *air* [81], *sound,* or *pictures*.

Further, if protecting functions are in focus, then *tensions* in the façade material can be sensed. In contrast to extrinsic systems, intrinsic or pre-programmed systems can also work *without* additional *sensors* [3]. Related to the sensor input, the **trigger event** plays an important role in designing AFs. Here, ordinary scenarios [54] such as *temperature* changes [59], *precipitation* [19], *humidity* [47,59], *wind speed* [59], *mechanical loads* [47], *sound* [59], *air quality* [47,59], *objects* [59], *occupant/user* preferences [42,81], *time triggers*, *neighborhood trigger* [81], *electricity consumption* [81], *grid trigger* [81], *light/solar radiation* [47,59], and *glare/sun location* [3] or *exceptional* events [54] such as a *hurricane, flood, fire, earthquake,* or *explosion* can trigger the adaptive reaction.

When adapting to such an event, the properties of the façade change. This leads to the description of the different **types of adaption**, which can be further distinguished between different types of *movement* [59] such as *transforming*, *translating*, *rotating,* or *scaling*, and changes in *transparency*, *color*, *stiffness* [42,54], or *texture* [59]. This adaption happens in a certain timeframe, which is defined as the **adaption time** and is further distinguished between *seconds, minutes, hours,* or *days*, *seasons*, *years*, and in some cases even *decades.* [21]

To enable the adaption, most actuators are integrated into the façade design. Here, different **types of actuators** can be used, such as *magnetic* [55], *pneumatic*, or *hydraulic* [59] actuators. *Chemical* [55], *electrical* [67], *thermal* [47], or *natural/biological* [55] actuators are also possible. Even if this categorization at first glance applies especially to extrinsically actuated systems, the intrinsic systems frequently mentioned in the literature can be assigned to these actuator types as well (e.g., shape memory alloys can be thermally actuated).

Table 2. The solution set of AF design parameters refined from the initial draft in [24], * cells highlighted in grey present a sub-set of "movement" as a type of adaption.

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		
Adaptive function: Operation	Change	Conduct	Store	Convert	Separate	Connect					
Adaptive function: Flow	Energy: Heat flux, Sound, Solar radiation/Light, Mechanical loads, Wind, Fire	Material: Water, Air, Occupant/User, Objects	Signal/Information: Occupant/User, Vision, Sound, Color, Texture, Shape								
Type of adaption	Change in …										
	Movement*	Color	Texture	Stiffness	Transparency	Permeability	Conductivity				
	*Transformation	*Translation	*Rotation	*Scalation							
Type of actuator	Magnetic	Pneumatic	Hydraulic	Chemical	Electrical	Thermal	Natural/Biological				
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									
Sensor input	None	Light	Temperature	Moisture	Magnetic fields	Electricity	Wind	Air	Sound	Picture/Camera	Tension
Integration of adaptive element	Additional	Replacing									
Connection to HVAC	None	Air	Fluid	Electricity							
Position of the adaptive element	External	In between	Internal								

Parameters that have been added in comparison to the state of the art are highlighted by underlining.

Other classification approaches describe the biggest implemented **size of the adaptive element** and range them from single *materials* with mostly low technology readiness levels and *façade elements* with the size of a door handle through to *façade components* (fenestration size), bigger *façade systems/walls* [59], and even *building envelopes/whole buildings* [22], where the AF also includes the roof. As well as the size, the **position of the adaptive layer**—*external*, *in between* static layers, or *internal* [67]—also affects the visibility of the adaption [59]. The means of **integration of the adaptive element** can also be distinguished between AFs that are installed *in addition* to existing conventional façades (e.g., in front of a regular glass façade) and those that are integrated into the façade and therefore mostly *replace* existing ones [19]. A further important aspect to mention when dealing with AFs is the connection to the HVAC of the building. Here, connections for *fluid* (e.g., water), *air* [20], or *electricity* lines have to be considered, whereas intrinsically controlled façades can also work without any additional connection. The last characteristic is the **degree of** which the **adaptive reaction** is conducted. Here, a separation between *binary* and *gradual* reactions is established in the literature [21].

6. Deriving Methodical Decision Support for the Basic Evaluation Phase

Methodical support is derived in this section on the basis of the raised requirements and the developed sets of criteria.

6.1. Developing a Checklist for the Early Phase Decision Making

The checklist is developed by simply listing the AF-specific main characteristics that were identified in Section 4.1. A short version of the descriptions in Section 5.3 is added next to the main characteristics to increase the comprehensibility. The descriptions of the main characteristics fall back on the preparation work conducted in [23]. Figure 11 illustrates the checklist. Some free space for taking notes is also included at the end of the checklist.

Adaptive façade design checklist - Methodical support for the basic evaluation phase.

The following characteristics differentiate an adaptive façade (AF) from a conventional façade and therefore play a significant role in the design phases. This checklist is designed to consider the AF-specific characteristics in the earliest ideation and brainstorming sessions. To do this, simply tick off if you have taken the characteristic into account. There is also space for notes at the bottom of the sheet.

No.	Characteristics:	Describes…	Check?
1	Control system	… what controls the AF (e.g. computer control, intrinsic material properties).	
2	Goal of the adaption	… the benefit of the adaption, compared to a conventional façade (e.g. increased thermal comfort).	
3	Adaptive function	… the function of the façade that is realized to be adaptive (e.g. change the amount of solar radiation going through the façade).	
4	Type of adaption	… how the adaption is realized (e.g. through movement, change in shape or color etc.).	
5	Type of actuator	… the basic physical principle of the actuators integrated (e.g. pneumatic or magnetic actuators).	
6	Trigger event	… the event on which the adaption takes place (e.g. wind loads or sun location).	
7	Size of adaptive element	… qualitatively the spatial size of the adaptive building component (e.g. façade element, façade system or the whole envelope).	
8	Adaption time	… the reaction time of adaption (e.g. seconds, hours or days).	
9	Degree of adaptive reaction	… whether the adaption is adjustable gradually (e.g. on-off or gradual).	
10	User override permission	… whether the user can override the pre-set control strategy based on their personal preferences.	
11	Visibility of the adaption	… whether the adaption is visible (e.g. for the occupants or for passers-by).	
12	Sensor input	… what the sensors of the AF system measure (e.g. photons of light, temperature changes).	
13	Integration of adaptive element	… how the adaptive element is integrated into the façade (e.g. replacing or additional).	
14	Connection to HVAC	… the connection to the HVAC (e.g. via air or water).	
15	Position of the adaptive element	… the position of the adaptive element (e.g. outdoor, in between two façade layers, indoor, east, west, south…).	

Notes:

Figure 11. Developed checklist for the early-stage discussion of suitable design goals.

The checklist shown in Figure 12 shows which characteristics are specific to AFs and need to be considered in the earliest discussions in which suitable design goals and requirements for the whole façade project are derived. However, as this checklist focuses on the AF-specific characteristics, these of course represent only a partial set of the relevant requirements for an AF design project. This method is intended to be used in addition to existing lists of main characteristics that are already available for conventional façades [1] or more generally for products [26]. Because an AF can be assigned to the areas of façades as well as products, both lists can play an additional role for AF and should be considered accordingly (see Figure 12).

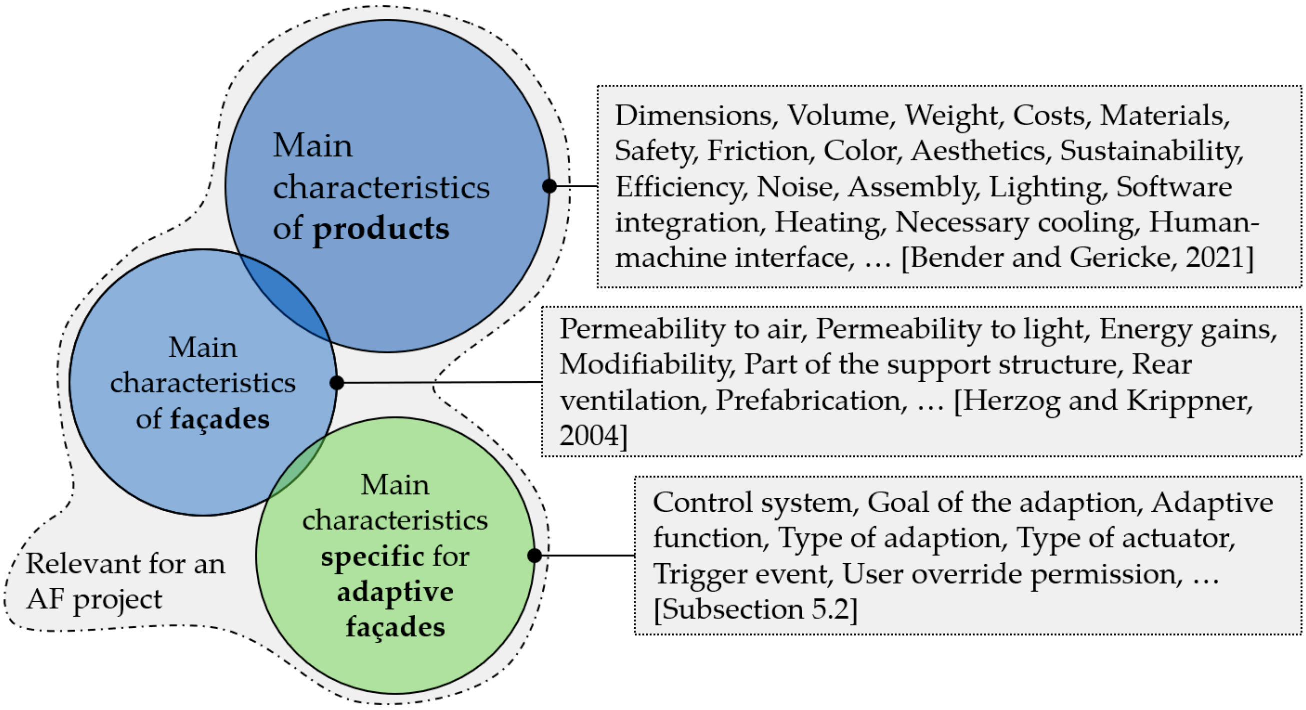

Figure 12. Schematic visualization of the relationships between the different sets of characteristics [1,30].

6.2. Implementing a Scientific Database of Adaptive Façades for the Early Phase Decision Making

Based on the expert interview described in Section 2 and the requirements for a suitable solution collection in Section 3.2, a solution collection is developed in this section. The interview also addressed different types of solution collections such as catalogs, lists, and databases. The consensus of the experts, which is also reflected in the requirements list, is that a digital database (Requirements I-1, III-1, and III-4) is best suited to the design task. This is because the content management system provides functions such as a dynamic (digital) search function and comparability between individual selected solutions, which is not possible with static catalogs or lists—even if they are presented in a digital format.

Because the database should be open access (III-3), it is currently realized in a web-based environment for easy access via a browser. The program structure implemented for this purpose is based on common web-based applications [89] and is shown in Figure 13. The end user's browser communicates with the server on which the application is hosted. This was programmed using the Python web framework Django (template for web applications). This in turn communicates with the PostgreSQL database program, which contains the AF dataset.

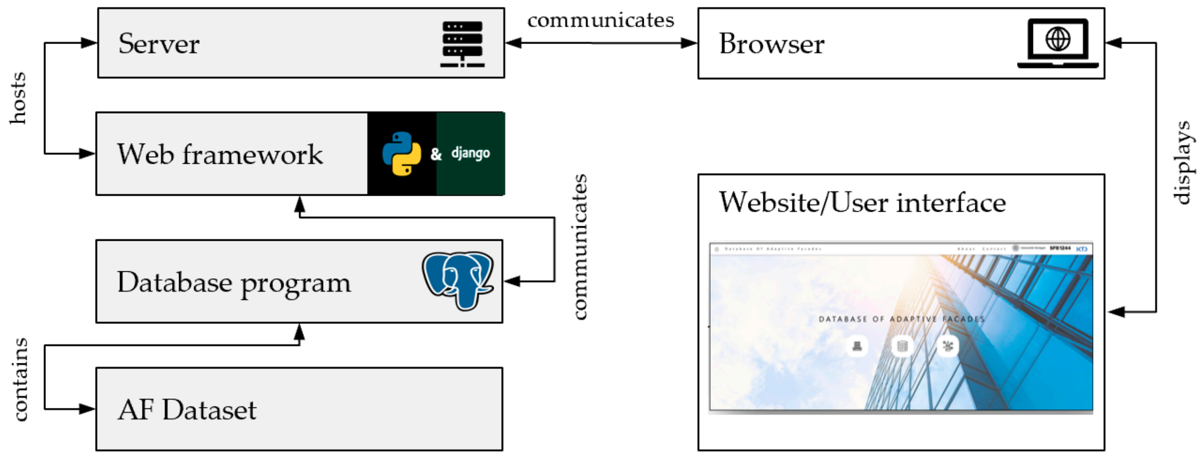

Figure 13. The program structure of the web-based database.

A more detailed structure of the implemented user interface of the database is presented in Figure 14. Opening the website leads the user to a title page. After the title page, three different paths can be followed. First, the user can continue to a page where an introduction and general knowledge about AFs can be read and where the criteria on which the database is structured (see Table 2) are introduced. This addresses requirement III-5. Second, a list of all the AFs in the database can be screened, or third, the search interface can be opened if specific AFs are in focus (I-2, III-1). The search can be performed using the name of the façade or the architect that was involved in the project. In addition, the identified design parameters can be selected individually so that the solutions are filtered and only the AFs with the respective valid parameters are displayed. Here, either one single façade or several façades can be selected. In the case of the single selection, the specific AF profile page opens: This displays both the specific design parameters and an image of the AF (III-2). Additional information such as the architect and the building location are also displayed (II-6), while links to project websites make it possible to quickly find more information regarding the AF (II-1). If more than one façade is selected, a comparison page opens where the selected façades are displayed next to each other with their respective images and design parameters (III-4).

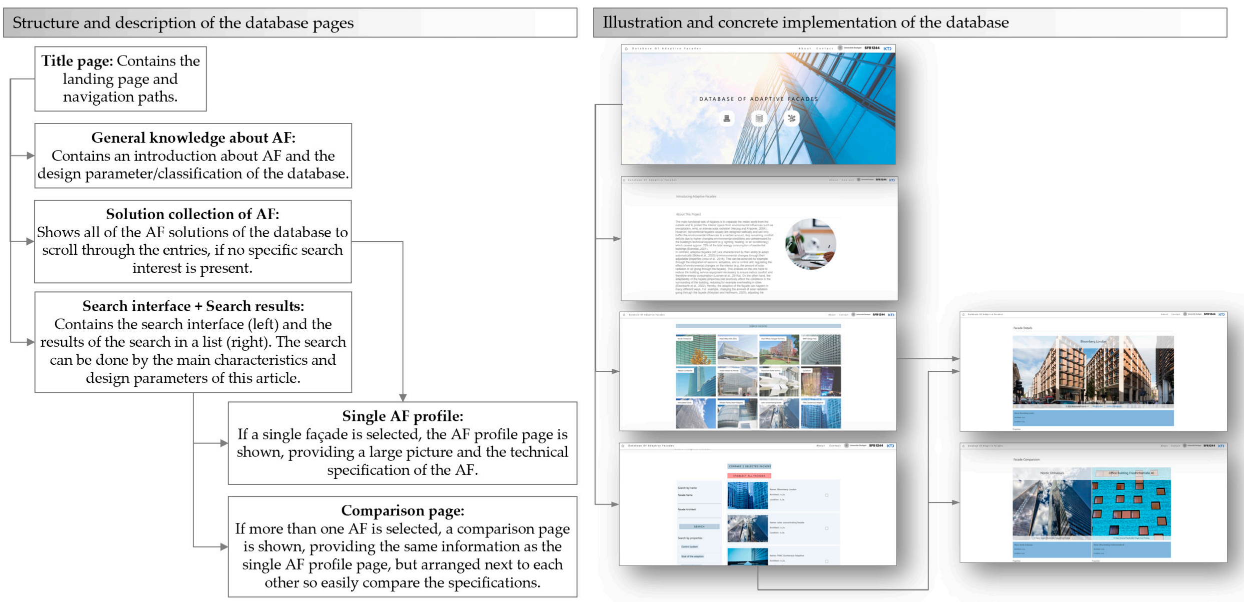

Figure 14. Structure and implementation of the user interface of the database of adaptive façades.

7. Evaluating the Research

After the developed decision support is presented, a support evaluation is conducted to check whether the requirements that were raised in Section 3 are fulfilled. For this purpose, the checklist, the database, and their criteria are evaluated differently. First, to evaluate the checklist and the list of main characteristics, expert interviews are conducted with façade engineers and architects that are currently involved in the development of AF systems [23]. The solution set of design parameters that forms the structure for the database is then evaluated by assigning 40 case studies to it [24]. Finally, the developed decision support is evaluated against the requirements raised in Section 3.

7.1. Evaluating the Checklist and the List of Main Characteristics

As presented in Section 4, checklists are already successfully used in different areas, and their usefulness mainly depends on their criteria. Therefore, the focus when evaluating the checklist is on its corresponding criteria. The criteria of the checklist were tested in relation to three different AF development projects that were in the preliminary design phase. According to the integrated design process framework by Voigt et al. [12], the preliminary design phase follows directly after the basic evaluation phase that is a point of focus in this article. The potential value of the checklist can thus be determined directly by comparing the results of the three AF projects with the identified criteria in this article (see Figure 15).

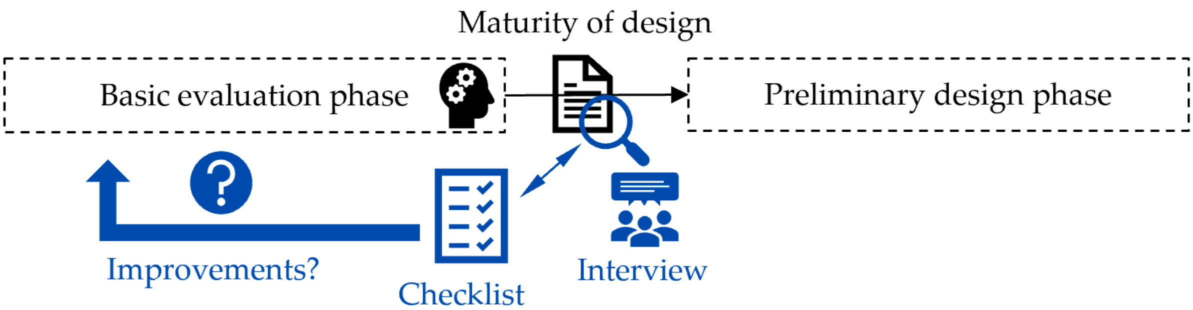

Figure 15. Set-up for evaluating the developed checklist.

As a reference, the three different case studies are introduced briefly [23] in the following. Where reference articles are already published, they are added at the end of the descriptions. In the first case study, two architects were interviewed. The second case study was represented by two architects as well, whereas the third case study was represented by an architect and two engineers (from the fields of building physics and energy engineering).

1. The first case study is an ultralight façade that is located on the ground floor of a building and made from textiles that are manufactured by layering glass and basalt fibers. These fibers are fastened by a matrix material similar to CFK materials. Its adaptability means that one whole side of the façade can move away to two adjoining sides when people interact with it. Therefore, the main functional task of a façade (to separate the inside from the outside) is temporarily dissolved.
2. The second case study adapts to the sun, with the position and intensity of the solar radiation acting as triggers for changing the shape of the façade. The façade is therefore built using a large number of solar sails that can reflect the sunlight back to the sky to prevent overheating in cities and regulate the amount of light that comes into the building. Initial investigations and analyses are reported by Jeong et al. [90].
3. The third case study deals with cooling the interior space with the help of solar energy. A three-step process and the material zeolite are used for this purpose. The important material property of zeolite is that it releases a large amount of heat when it is combined with water. The three-step process starts with wet zeolite. The material is dried with the help of solar radiation. The evaporating water (closed system) will then

be guided to a tank on the north side of the building (cooler surroundings), where it condenses again. When the sun moves and the zeolite cools down again (now dry), the water is guided to another tank inside the building where it can use the heat of the interior (different pressure level) to evaporate again. The steam (with the energy from the interior) will then be guided to the zeolite again, where it binds the water and releases the temperature back to the surroundings. The principle is also published by Schaefer et al. [91].

Figure 16 presents the evaluation results regarding the checklist and main characteristics. Here, in contrast to the previous limitation to the AF-specific characteristics, all of the identified characteristics from the literature were considered in order to gain possible further insights such as how frequently the AF-specific characteristics are named compared to the other criteria that were identified as being relevant for façades or products in general. The evaluation procedure started with the engineers and architects of the case studies being asked to name the relevant characteristics of their AF designs. The criteria that were named directly are marked as “mentioned and considered” in white in Figure 14. The checklist would not have provided any further support for these criteria. After the architects and engineers named their characteristics, the collection of characteristics (including the AF-specific characteristics) was shown to them. Feedback was then gathered, with the criteria being classified into three different categories. The first category was “not mentioned but considered”, which includes all the characteristics that have been already discussed in the project but were either only roughly discussed or were not focal points for the participants, as reflected by the fact that they did not name the criteria in the first place. As these criteria are relevant to the project, the checklist would provide support to the extent that all the relevant criteria are collected in one place. Especially interesting are the criteria that are marked as “not considered yet”. These criteria were revealed to be relevant to the AF project but have not (yet) been discussed or considered in the basic evaluation phase. This is where the checklist is of greatest value, as unnecessary iterations in the later phases of the design process could be prevented effectively. Criteria that are marked as “not relevant for this AF” are the criteria that were not relevant in the interview for that particular AF project. However, as these vary between the different AF projects, they were still considered as being relevant for the checklist.

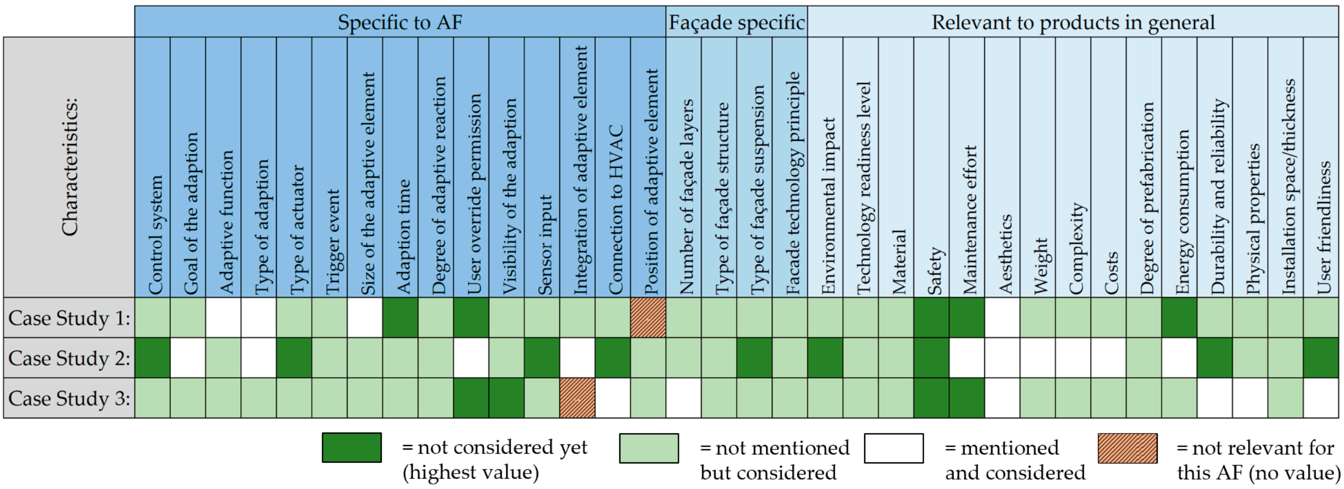

Figure 16. Evaluation results of the identified characteristics in three AF projects, adapted from [23].

Analysis of the results also enables the following statements to be made regarding the fulfillment of the requirements raised in Section 3:

1. The **initial completeness** (requirement 1) of the criteria set is seen as achieved because only one of the characteristics named by the participants ("surface of the façade") was not represented in the list of main characteristics. As this characteristic is also valid for façades in general, it is not added to the checklist with only AF-specific characteristics.
2. **Comprehensibility** (requirement 2) can be approved, as this forms the basis for the participants to confirm the relevance of the respective characteristics.
3. The **consistency/logic** (requirement 3) of the criteria is very good in terms of how many of the characteristics were relevant for the AF projects. The results when considering all the criteria are 0.97 (33/34) for the first case study, 1.0 (34/34) for the second case study, and 0.97 (33/34) for the third case study. Considering only the AF-specific characteristics, the values change to 0.93 (14/15) for the first case study, 1.0 (15/15) for the second case study, and 0.93 (14/15) for the third case study.
4. **Objectivity** (requirement 3) of the result was targeted by considering all the literature found to derive the set of main characteristics. Similarly, the evaluation in the context of the three case studies was conducted without communicating the objective of developing a checklist to the participants in advance. However, despite great efforts, it cannot be ruled out that aspects such as the naming of the main characteristics were based on the authors' perspectives.
5. As the checklist only includes AF-specific characteristics, the **product (type) specificity** (requirement 4) can be approved.

In general, the evaluation shows that the developed checklist with the AF-specific characteristics can provide added value to the discussions in the basic evaluation phase of an AF project. This is shown both by the evaluation of the specific requirements and by the feedback of the participants in the interview, who approved that such a checklist would have been helpful in the early discussion of the AF project.

7.2. Evaluating the Set of Design Parameters and the Initial Form of the Database

The first step in evaluating the database is to check if the criteria and therefore the classification approach fulfill the requirements raised (mainly requirements II-2, II-3, II-4, II-5). Therefore, 40 AF case studies are assigned to the classification approach of the design parameters [24]. This check is necessary as the set of design parameters is currently based on classification approaches from the literature and extended due to dependency on the main characteristics. As can be seen in Figure 17, the assignment of 40 case studies to the design parameters reveals the first insights into the state of the art of AFs and the content of the database. The incidence of each design parameter is also shown in Figure 17, right behind each design parameter. Although the authors did not actively influence the selection of the AFs, and most of the AFs considered were those that also appear in the classification approaches in the literature [3,48,52], the first aspect to recognize is that most of the AFs here have a high technology readiness level. In other words, these are AFs that have already been implemented as a complete AF system (29/40).

If an AF implements several design parameters in the same category (e.g., adaptive function: changing solar radiation and changing the vision through the façade), then both parameters are of course added. This results in a higher sum total of entries for this category than for another in which only exclusive options are possible (e.g., degree of adaptive reaction). Nevertheless, the relative share of each design parameter within its category is still identifiable.

Figure 17. Assigning 40 AF case studies to the design parameters (sorted by frequency), from [24].

Figure 17 shows that most of the AFs adapt their functionality with regard to changing the solar radiation (35/40) and vision (30/40) through the façade. Accordingly, the goal of the adaption most often is related to visual (34/40) and thermal (30/40) comfort. The trigger event in 21/40 cases is the sun's location, whereby the intensity of the solar radiation also plays a significant role (21/40). These often correlate with each other but can sometimes also be detected differently, for example using cameras. Most of the AFs analyzed in this study change their properties due to moving parts of their system, such as blinds. In this category, 21/40 AFs implement rotational movement and 14/40 translational movement.

According to the adaptive function and the goal of the adaption, most of the AFs sense light (29/40) or temperature (11/40). The adaption then happens in a matter of seconds (17/40) or minutes (29/40).

Nearly all of the analyzed AFs are controlled extrinsically (36/40), requiring an extra control unit. A total of 35 out of 40 AFs adapt their properties gradually, whereas the position of the adaptive layer is most of the time applied externally (27/40) and additionally (28/40). The lack of integration here potentially highlights the need to find better ways of integrating the AF functions into the façade [92]. The visibility of the adaption is accordingly mostly visible (37/40). Electric actuators (25/40) are often used and the behavior of around half of the façades (17/40) can be adjusted by the occupants/users. Finally, at least 10/40 AFs are connected via electric lines with the HVAC system of the building. As can be seen, the information on the latter characteristics was fragmented in the literature. For example, the information on the user override permission is lacking for 10 of the 40 analyzed AFs, resulting in only 30 meaningful entries. After assigning the AF case studies to the set of design parameters, it was found that none of the AFs had exhibited further AF-specific design parameters within the identified main characteristics considered here. This suggests that an initial degree of completeness is achieved.

To summarize the results of the support evaluation regarding the database, it can be seen that many of the requirements raised in this article could already be addressed (referring to the descriptions in Section 6.2). Further, the requirements with regard to the product specificity (II-2), consistency (II-3), (in-) dependency (II-4), and initial completeness (II-5) of the classification criteria are addressed by the systematic preparation of the design parameters in the previous section. Figure 18 shows the summarized evaluation. Requirements that have already been addressed and implemented are presented in dark blue, those that have been partially addressed and implemented are shown in light blue, and those that have not yet been implemented remain white. The number of façades and criteria are also listed, similar to the evaluation of the state of the art in Section 4.

Requirements:	I Methodical		II Content							III Visualization				
	1	2	1	2	3	4	5A	5B	6	1	2	3	4	5
The developed database							40	17						

= fully implemented = partially implemented = not yet implemented

Figure 18. Evaluating the developed web-based database against the requirements raised.

It can be seen that most of the requirements are already implemented and evaluated. Currently missing are the questions related to a usability study related to the integrated design process of AFs.

8. Discussion, Conclusions, and Future Research

Based on the presented results and the support evaluation in the previous section, this section will provide a discussion of the results, conclusions, and possible further research steps. The research objective of the article was to *derive consistent methodical support for the definition of suitable design goals and decision-making in the basic evaluation phase of an integrated design process.* The basic evaluation phase was therefore analyzed first, with checklists and solution collections identified as suitable methods for the featured steps. For the checklist, this was performed via reference scenarios in mechanical engineering and expert interviews were also conducted for the database. Afterwards, requirements were raised to define the support that is needed for the decision making in the basic evaluation phase of the integrated design process of AFs. Based on the requirements, it was possible to evaluate the existing solutions and reveal that suitable decision support is not yet available. The evaluation showed that in various use cases, both in mechanical engineering and in civil engineering, there are existing checklists that provide corresponding main characteristics for decision making—but no AF-specific checklist yet exists that has a sufficient degree of consistency and initial completeness. In the case of solution collections, it became apparent that the existing approaches were mostly implemented non-digitally and are therefore difficult to expand/update, have poor usability with high data volumes, and the classification structure does not meet the requirements identified in this article (e.g., consistency, initial completeness, or AF specificity). Moreover, the few existing digital solutions are characterized by not being specific to AF but containing a variety of different façade types, meaning that they lack transparency in terms of which façades are adaptive and which are not. Subsequently, the aforementioned gaps were addressed through the systematic development of the content for the checklist and the classification/structure of the database. For this purpose, two previously published conference studies [23,24] on the main characteristics and design parameters of adaptive façades were referred to. The results were revisited for the purpose of this article and further developed. The resulting sets of criteria provide the basis for the checklist and the database. Due to the existing checklists in the area of product development and conventional façades, the focus was placed on the characteristics that apply specifically to AFs. Although the completeness and objectivity of the checklist criteria cannot be ensured completely, the support evaluation shows that a high degree of completeness and objectivity can be assumed. Comprehensibility, logic, and consistency were also approved in the support evaluation, which indicates that the developed checklist meets the identified need.

Regarding the solution collection, the requirements showed that next to catalogs or lists, databases in particular were best for meeting the requirements. The set of design parameters was therefore used as the structure for the content of a database. Furthermore, the database was implemented digitally, and 40 case studies of AFs were assigned to it. The assignment approved the solution set of design parameters, as none of the AFs had any design parameters that were different from the solution set developed in this article. Of course, this is only valid for already implemented AFs, as the ongoing development and research in this field might bring new AFs with new design parameters. However, the solution set of design parameters presented here can already inspire the development of new types of AFs, which makes the added value of adaption even more versatile. Looking at the area of adaptive functions, for example, new approaches can be quickly derived by combining individual entries. For example, ideas can be developed in which sunlight is stored using fluorescence to illuminate the streets at night. Additionally, sunlight could be guided from the façade to deeper rooms using mirrors or glass fibers, reducing the need for lighting inside the building. The wind resistance of a tall building can also be changed adaptively to reduce the necessary mass of the building structure, or access (e.g., for the fire brigade) to the individual floors can be facilitated in the event of catastrophes (e.g., house fire).

Due to the digital implementation of the database, nearly all of the functional requirements raised could be addressed. Still, it cannot be seen as fully evaluated because an expert usability test in the context of the overarching integrated design process is necessary to scientifically approve the value. Such a usability test would also include the use of the checklist to test the interaction of the two methods. This presents one of the possible future steps. Furthermore, the database is planned to be uploaded to the internet as soon as hurdles regarding the security of the software, financing of the hosting, and legal constraints have been clarified. The link will be provided in the author's ResearchGate profile (https://www.researchgate.net/profile/Michael-Voigt-2, accessed on 26 February 2023). Meanwhile, the number of AF entries will be further increased to increase the database's value. In addition to expanding the content of the entries, it would also be conceivable to extend the technical and functional considerations of this paper to include architectural and aesthetic characteristics, quantitative data such as the environmental impact, costs, or energy consumption of the systems, and even CAD models. However, these data are difficult to obtain from the literature, as AFs have so far mostly been stand-alone solutions. The corresponding effort could be of interest for a commercial database but was not within the scope of this scientific work. Widening the scope, the AF-specific characteristics here could also be used to extend the existing methodical support (e.g., BIM) for conventional façades so as to quickly make these applicable to AFs.

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