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DOI
10.3390/su122310118

Publication date
2020

Document Version
Final published version

Published in
Sustainability

Citation (APA)
Juaristi, M., Konstantinou, T., Gómez-Acebo, T., & Monge-Barrio, A. (2020). Development and Validation of a Roadmap to Assist the Performance-Based Early-Stage Design Process of Adaptive Opaque Facades. *Sustainability*, *12*(23), 1-28. Article 10118. https://doi.org/10.3390/su122310118

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Article

Development and Validation of a Roadmap to Assist the Performance-Based Early-Stage Design Process of Adaptive Opaque Facades

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Received: 6 November 2020; Accepted: 1 December 2020; Published: 3 December 2020

Abstract: Adaptive Opaque Facades (AOF) is an innovative concept with potential to achieve low carbon energy buildings. However, so far AOF are not integrated in the construction industry. One remarkable issue that designers have when dealing with alternative low-carbon technologies, such as AOF, is the absence of previous built experiences and the lack of specialised technical knowledge. Design roadmaps can be convenient solutions to guide pioneer low carbon technology applications. This work presents a roadmap to assist the performance-based early-stage design process of Adaptive Opaque Facades. Previous research developed new approaches and tools to assist on the construction definition of AOF, so that their adaptive thermal performance was considered when specific design decisions needed to be made. The roadmap presented in this paper organises the implementation sequence of each methodological approach and tools in different design stages, which aims to provide a holistic design approach for AOF. The usability of the roadmap was validated in a workshop called "Performance-based Design and Assessment of Adaptive Facades" with master students representing the target group of this roadmap. Even though these students had never heard about AOF before, they could successfully design, define the early-stage characteristics of an AOF and quantify the thermal performance of their AOF designs. The roadmap was proven to be a useful support, which might make the implementation of AOF more approachable in the future.

Keywords: adaptive heat transfer; adaptive insulation; switchable coatings; thermal performance; low carbon energy building design

1. Introduction

1.1. Background

Buildings are responsible for 40% of the global energy consumption [1]. A design paradigm change is needed to reduce their environmental impact so that European low-carbon targets are accomplished [2]. Design tools and novel design method approaches can be useful to integrate novel technologies in the construction industry, as they enable designers achieving information to support design decisions when they have no previous built experiences. That is why the research environment is not only focused on developing low carbon technologies, but also on supporting the design process. For instance, Attia et al. developed a tool to assist on Zero-Energy Building Design and validated its usability through a workshop [3]. Toolboxes offer similar assistance, but in their case, they show designers how to get and process the information to take design decisions, as Konstantinou does to support facade refurbishments [4]. There are also numerous works about Parametric Design Processes. These works explain how to improve and/or optimize the design by systematically varying one/several parameter(s). Several Parametric Design Processes have been developed to facilitate the design of bioclimatic kinetic envelopes, as they can inform about the performance effects when facade shape is changed autonomously [5–8]. They are also applicable to responsive skins or adaptive transparent facade design so that designers can quantify the impact of applying these facades in different climates and orientations [9,10] and can understand the consequences of changing some of the responsive technologies features or characteristics [11]. Similarly, simplified simulation methodologies aim to provide fast and simple ways to assist in the selection of appropriate building components and system during early design stages [12–14]. From a more holistic perspective, design frameworks provide criteria and design strategies to assist on design process decisions. Among them, Looman developed a design framework to assist on the understanding of energy concepts for climate-responsive architectural designs, where building envelopes are also considered [15]. Prieto et al. presented a framework to assist designers in the solar cooling technologies integration in building envelopes [16] and several researchers developed different frameworks to consider the application of climate responsive envelopes [5,17–22]. Roadmaps can also be valid methods to consider holistically specific technologies in the design process, as they propose a workflow and point out the particular design-considerations and constrains. They proved to be useful to promote the achievement of zero- and positive-energy buildings and neighbourhoods [23,24] or to consider energy efficiency in residential building envelope retrofitting [25]. Furthermore, hierarchy process-based systems and mapping systems can be helpful when performing life cycle assessment of building technologies at early design stages [26,27].

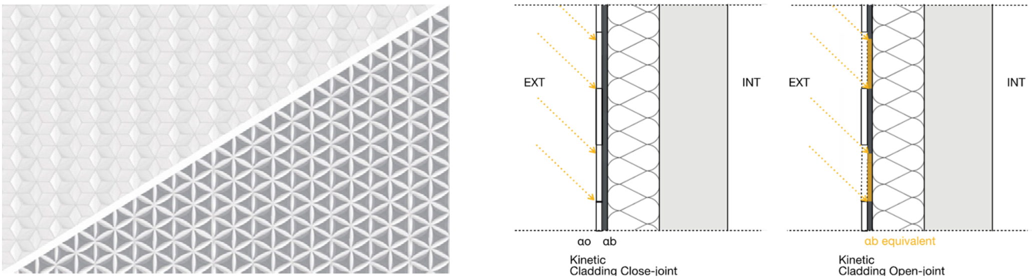
Besides, well-performing facades are crucial for sustainable building design, as they are the physical barriers between indoor and outdoor environments and, as a consequence, buildings lose and gain energy through the envelops. Thus, the quality of facades directly affects the obtainment of comfortable indoor conditions and thermal energy use, which has encouraged the development of low-carbon innovative technologies for facade application. Adaptive Facades are among the most promising options, as they have the ability of reversely and automatically control some of their features, characteristics and behaviours under different boundary conditions. So far, the most studied Adaptive Facades manage autonomously solar heat gains and daylight [28]. They do so through kinetic solar shading devices [29–32] and smart glazing [33,34]. A less explored adaptive facade typology is Adaptive Opaque Facade. So far, they are being developed in the research environment and architects and facade engineers have no experience and specialized knowledge on their design or building integration.

1.2. Adaptive Opaque Facades: An Innovative Concept Born in the Research Field

Adaptive Opaque Facades refer to the opaque part of the vertical building envelope and they have the ability to reversely and automatically control:

- **heat gains** on the outer layer, through the variable solar absorptance of the cladding can be obtained by integrating thermochromic coatings [35–38] of automated Kinetic Claddings (see Figure 1);
- **heat transfer**, either by (a) air-flow exchange between different facade elements (see Figure 2) [39–45] or (b) by conduction, by modifying the thermal heat transfer of facade elements (see Figure 3) [11,46–54];
- **thermal storage,** by integrating materials which have latent heat storage at ambient temperature [55–58];
- **humidity air-content** [59–62].

There are some examples of AOF built within the research environment to test experimentally their performance. At facade component level, researchers produced prototypes which controlled the thermal heat transfer, such as the prototype of a Removable Insulation component [53], a Close Loop Dynamic Insulation (see Figure 3) [63], a Permeodynamic wall [64], or a Bi-directional Thermodiode component [65]. The last two components were also assessed in calibrated test cells [39–43]. Besides, at least seven research works were found in literature which tested AOF at system level in calibrated test cell [44,66–71] and were mostly focused on evaluating their adaptive thermal and ventilation performance. These last facades are also known as Parietodynamic walls (see Figure 2).



(**a**) (**b**)

Figure 1. (**a**) The solar absorptance of Opaque Facades can change under different boundary conditions when kinetic claddings are integrated in Adaptive Opaque Facades (AOF). They have open and close position. Kinetic claddings are still in conceptual phase [59]; (**b**) the solar absorptance of automated kinetic cladding is conditioned by (i) the materials of outer and inner claddings and (ii) the geometry of the external cladding. When the Kinetic Cladding is in close-joint configuration, the solar absorptance of the outer cladding layer material (αo) corresponds to the solar absorptance value of the AOF. When the Kinetic Cladding is in open-joint configuration, the material in contact with the insulation layer is the one which captures solar radiation [72].

(**a**) (**b**)

Figure 2. (**a**) Parietodynamic concept: Parietodynamic walls have an air cavity between the external cladding and the insulation/inner wall element. This inner element is crossed by an air duct that connects the cavity with the interior environment. The air which is transferred from the outside to the inside can be controlled according to outside and inside conditions and fans are used to force the air-flux. In this way, the supply air can be pre-tempered by solar heat gains (when the heat flux is outdoor–indoor). When this connection is closed, it acts as a regular insulation element. In summer conditions, overheating can be dissipated to some extent by enabling the energy exchange when the indoor temperature is higher than the external air temperature [45]. (**b**) Experimental tests of different Opaque Ventilated Facades have been carried out to characterize better the behavior of Opaque Facades under different boundary conditions [73].

(**a**) (**b**) (**c**)

Figure 3. Closed-loop dynamic insulation, also known as active insulation, can control the heat flux direction and intensity [46,74]. When the ventilation is not working, this component acts as a regular thermal barrier between indoor and outdoor. When the ventilations are working, heat transfer is encouraged. (**a**) Schematic drawing of active insulation; (**b**) vertical section of active insulation. There is no air or water exchange between indoor and outdoor environments. (**c**) First monitorization campaigns of adaptive insulation.

However, even when the product development of dynamic opaque technologies will be mature enough for their building application, the construction of Adaptive Opaque Facades will still be challenging if architects and facade engineers do not have enough specialized support information to design them. Without this support, the design of Adaptive Opaque Facades is especially difficult due to their dynamic behaviour. The integration of dynamic technologies implies that facades' performance might not be directly related to metrics calculated from the physical characteristics of materials (such as U-value) and moreover their performance is conditioned by the local boundary condition of each application and on the way the dynamic properties are controlled [75].

To face this challenge, recent research has developed novel design methods and tools which would assist in:

- detecting appropriate Adaptive Facade Responses according to the climate and building use [76];
- selecting responsive technologies that could be applied in these facades [77,78];
- understanding the way the technology application order could alter the thermal behaviour [59];
- assisting designers through building simulations to analyse the thermal performance of different AOF typologies and design options [72].

Furthermore, Andrade et al. analysed qualitatively the design implications of integrating auto-responsive elements in Opaque Facade systems in refurbishment [79]. More recently, Soudian et al. proposed a qualitative assessment of Adaptive Facades (both for transparent and opaque parts) based on quantitative metrics, with the aim of giving additional useful information to designers when analysing the constrain of the environment and building context, defining a responsive operation section and selecting technologies [22]. This work, in contrast with the aforementioned design methods, had a holistic design perspective, as does the current paper. However, even if Soudian et al. used quantitative metrics to assist on the design decisions, this did not provide the calculation methods and tools to quantify the performance of different design options in each design stage. This is a key limitation when considering the thermal performance appropriately in the early-stage decision-making process.

All in all, the aforementioned methods and tools are useful to assist on different design decisions. Even though, as mainstream facade design workflow does not serve to consider the dynamic operational principle of AOF, first experiences on AOF design might be too complicated if there is not a unified holistic design process which assists designers both on technology selection and on the quantification of AOF performance. Moreover, a correct implementation order of design methods and tool application is essential to propose effective AOF.

1.3. Research Scope and Objectives

This research proposes and validates the usability of a design roadmap that assists architects and facade engineers during the early-stage design process of AOF, in such a way that the thermal performance is considered appropriately in the early-stage decision-making process. To do so, useful design approaches and tools developed for AOF definition and quantification of AOF performance are compiled, ordered and integrated in a unified workflow.

Section 2 outlines the methodology which was followed to develop the design roadmap and presents the workshop which validated its usability through the Usability test method [80]. The third part of the paper presents the roadmap and illustrates the way designers should use it to take early-stage design decisions of an AOF for a given climate, building type and indoor space configuration. In Section 3.2, the results of the workshop are presented and the AOF designs proposed by students are outlined. This section also discusses the thermal performance of AOF designed by students. Afterwards, the survey results carried out in the end of are presented, which aimed to evaluate the application and usability of the roadmap. Finally, the results are discussed, main conclusions are drawn and further works are outlined.

2. Materials and Methods

2.1. Roadmap Development: Compilation of AOF Design Methodologies and Tools and Organization Criteria

The particular features and characteristics of AOF require a specific design approach which is able to consider the combination of (i) local boundary conditions and (ii.a.) the control system—for active facades—or (ii.b.) operational principles of smart or multifunctional materials. These combinations determine the final performance of Adaptive Facades. In this context, designers need to apply design approaches which are specific for AOF in order to understand how their proposed construction is behaving under different boundary conditions. Table 1 presents the compilation of reference documents according to the support that they can provide for AOF design and it indicates which design task/decisions can be informed. These documents are useful to decide which type of AOF should be applied, where AOF should be placed, to select suitable technologies and AOF typologies, to assist on the quantification of the thermal performance and to evaluate if the achieved performance benefits deserve the additional complexity that implies the integration of dynamic technologies.

Table 1. Support documents and tools to assist designers in the construction definition of AOF.

Design Decision/Task	Reference Document/Tool	Provided Support for Designers
Application of Adaptive Opaque Facade (AOF)	Dynamic Climate Analysis tool [76]	Tool to understand if the climate has the potential to apply AOF Tool to detect which thermal behaviour has potential to be adaptive according to the climate
Placement of AOF	Dynamic Climate Analysis tool [76]	Tool to check if the orientation and inclination of the facade is suitable to place AOF
Technology selection	Qualitative analysis of promising materials and technologies for the design and evaluation of Climate Adaptive Opaque Facades [77]	Qualitative Analysis of available responsive technologies to understand the construction implications of applying them as part of the facade systems
	Smart and Multifunctional Materials and their Possible	Classification of the dynamic behaviours that can be achieved for each material

	Application in Façade Systems [78]	family and the design consequences of their facade integration
	Exploring the potential of Smart and Multifunctional Materials in Adaptive Opaque Facade Systems [59]	Methodological approach to select adaptive and static technologies and their position in the multi-layer facade construction system, so that the aimed dynamic thermal behaviour is obtained
Selection of AOF typology	Dynamic thermal performance simulation based on current technological state for assisting on the design of Adaptive Opaque Facades [72]	Classification of possible AOF typologies according to current technological state of static and responsive technologies
Quantification and evaluation of the thermal performance	Dynamic thermal performance simulation based on current technological state for assisting on the design of Adaptive Opaque Facades [72]	Methodological approach to quantify the thermal behaviour of different AOF typologies (Simulation Workflow) and to select the best-performing ones according to selected metrics Methodological approach to quantify the impact of different design decision and to understand in which way the thermal performance of proposed AOF improves the Reference Static Facade which was established as a benchmark

The design decisions are ordered in a certain way to avoid the detailed analysis or calculation of suboptimal solutions. In order to illustrate how the information on Adaptive Opaque Facades can support the design process, a roadmap was developed. It proposes a design workflow which orders the design steps and indicates when the iterative design-processes are needed. Each design step of the roadmap is structured in the following way:

- **Explanation of the key points which condition the design step**

The roadmap summarizes the main design steps and it is organized according to the key considerations. Key considerations include (i) design constrains, (ii) benchmark definition, (iii) available responsive technologies, (iv) facade typologies and aesthetics, (v) desired dynamic thermal behaviour, (vi) control system and (vii) the evaluation of the thermal performance. The proposed design support roadmap for AOF consists of a seven-step procedure and enables the construction definition at early design stages, prior to prototyping or mock-up testing procedures.

- **Specific considerations that define main design inputs of AOF**

The design of AOF have some common considerations with mainstream static opaque facades, such as contextual and architectural conditions, clients' and legal requirements and available technologies and facade typologies. Moreover, there are additional conditioning factors which are related to the dynamic nature of AOF. For this reason, the design roadmap shows the necessity of considering (i) possible AOF roles, (ii) meaningful physical properties for different dynamic behaviours, (iii) detecting possible control/activation system; and (iv) describes the key considerations to clarify if the dynamic behaviour of AOF leads to an enhanced thermal performance or not.

- **Detection of the methodological approaches or tools which can assist designers at each design step**

As stated in the previous paragraph, some specific considerations are common to static opaque facades. However, applicable design methods might differ for the same design steps due to AOF working principle. For instance, the AOF will consider the climate conditions, but mainstream climate analysis does not capture the climatic characteristics which condition the correct design of AOF [76]. For this reason, the particular AOF design methodologies and tools which serve to assist at different design steps were detected in scientific papers. The roadmap summarizes their content and highlights the support information they can provide.

- **Expected output at each design step**

The main output would be the construction definition of an AOF, prior to prototyping or mock-up testing procedures. To achieve it, designers start defining general characteristics and features of AOF (e.g., facade orientation, adaptive role, etc.) and through the roadmap, dynamic technologies and building materials are selected, facade typology and its control are defined and the thermal performance of designed AOF is quantified. According to the obtained outputs, designers might need to carry out iterative design processes to enhance their facade design.

The resulting workflow is illustrated in a design roadmap, which is presented in Section 3.

2.2. Validating the Usability of AOF Design Roadmap: The Workshop "Performance-Based Design and Assessment of Adaptive Facades"

The applicability of the developed roadmap exposed in Section 3 was tested by students of the Master's Degree in Environmental Design and Building Management, as the proposed design method is intended to be used by architects, designers and stakeholders of Facade Engineering and/or Environmental Design in Architecture and, therefore, they represented the target group. A workshop of three days called "Performance-based Design and Assessment of Adaptive Facades" was organized in the School of Architecture of the University of Navarra (Spain), which consisted of (a) lectures about Adaptive Facades and (b) a practical exercise, i.e., the design and assessment of an Adaptive Opaque Facade for a given climate and building type (the task is summarized in Appendix A). Twenty-one students in groups of three (so, seven groups) participated in the workshop in February 2020. To demonstrate the suitability of the roadmap, proposed climates and building use were previously checked by the authors in order to verify that AOFs offer an opportunity to improve the benchmark static facades. Moreover, to promote different aesthetical solutions, two different contexts were selected for each location: the historical city centre and a recent commercial urban district.

To assess the design roadmap without missing any key point, a qualitative validation was carried out structured as a survey, where respondents were the participants in the workshop. The aim of this survey was to asses that the roadmap serves beyond the case study that was undertaken during the workshop. The important aspects to validate the roadmap were related to (a) the completeness of the provided material at each design process, (b) the clarity and usefulness of the methodological approaches and tools developed for each stage and (c) the relevance of the roadmap key points. In particular, to test the usefulness of each tool and method, the survey questions in this regard followed the Usability test method [80]. The detailed set of questions corresponding to the validation are compiled in Appendix B. Additionally, the thermal performance of AOF designs proposed by students as final solution served to verify that the roadmap is useful to design AOF which have an enhanced thermal performance with respect to the reference static opaque facade.

3. Results

3.1. The Design Support Roadmap

Figure 4 presents the AOF design roadmap in the form of a flowchart. The flowchart includes the questions and considerations at each design stage and it takes from Table 1 which methodological approach or tool can be useful to support design decisions. The following section outlines the design input and output of the aforementioned support documents and explains how they assist in making design decisions.

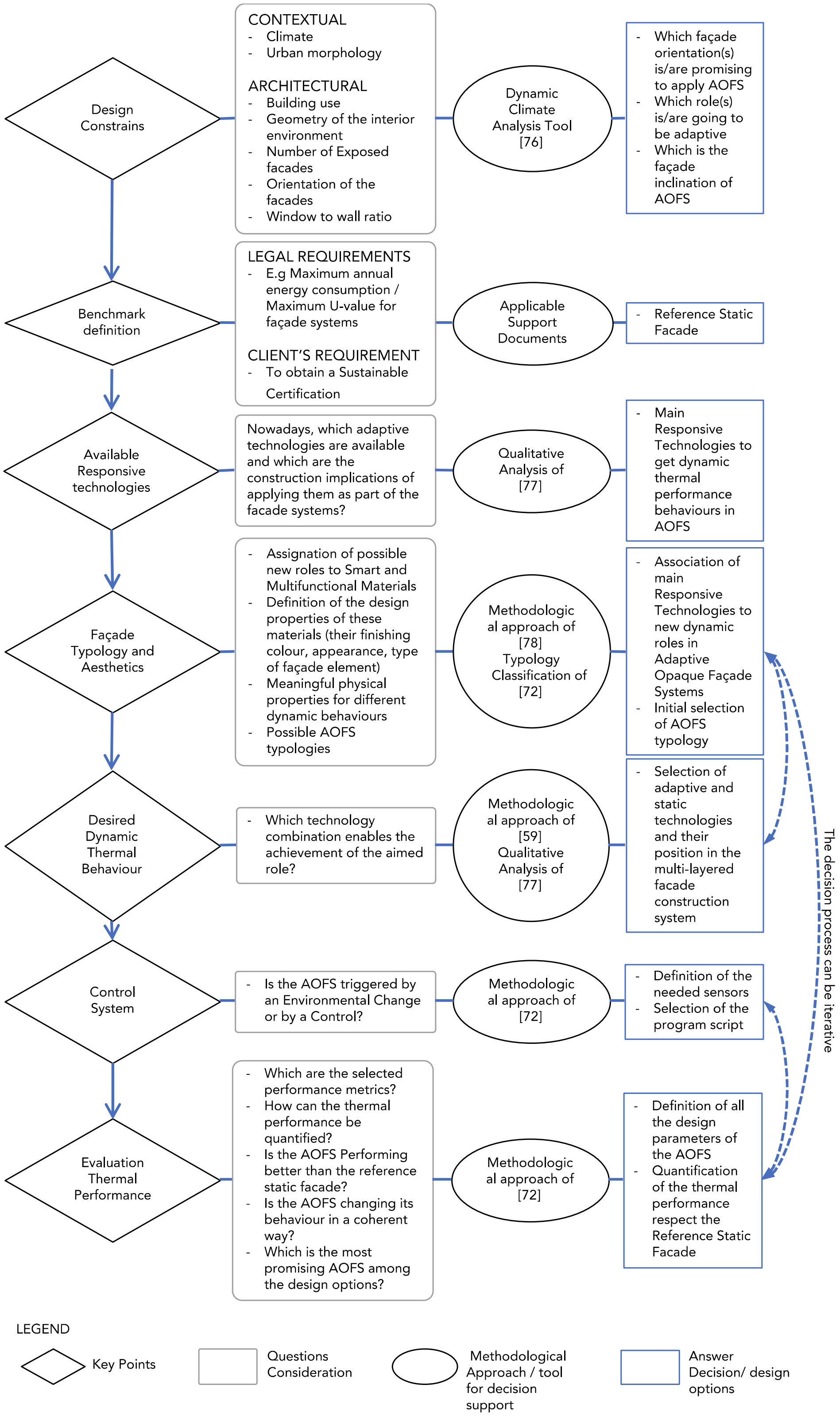


Figure 4. Roadmap to assist the performance-based design process of Adaptive Opaque Facades.

The first step of the roadmap is to analyse the contextual and architectural conditions, in order to detect the potential characteristics and constrains of the building environment. AOF have a particular requirement: adaptiveness will be promising according to boundary conditions. Hence, climatic conditions play an important role. However, the particular heat transfer mechanism of AOF makes the application of standard climate analysis unsuitable. In [76], a new methodological approach was proposed called dynamic climate analysis (DCA), of which the working principle is briefly summarized in Table 2. This approach extracts relevant transient information from weather files when designers define the location, geometry and the orientation of the Opaque Facade Systems and narrows down the preferable Adaptive Opaque Facade Responses (AOFR). With the information that is available at early design stages, DCA is able to estimate the rate of preferred adaptive thermal behaviors, without detailing and simulating specific dynamic technologies. Therefore, designers could use the DCA approach to obtain in this first step the facade orientation(s) that offer(s) suitable conditions to place an AOF and the preferred AOFR. In this first step, it is also possible to test by DCA tool use if there is a facade inclination which can improve the AOF performance.

Table 2. Design support provided by Dynamic Climate Analysis [76].

Input	Design Support	Output
- Hourly Outside Air - Temperature (°C) - Hourly Incident Solar -Radiation (kWh) * - Area of the Opaque Facade which might have an Adaptive Response (m^2)	- Tool in a form of an Excel file (for temperate coastal climates and residential buildings) - Methodological Approach to analyse dynamic features of the climates for other climates/building uses	- Over a year, the rate at which the AOF should be in insulation mode vs. heat dissipation mode. - Over a year, the rate at which a cladding with low solar absorptance is beneficial vs. a cladding with high solar absorptance is beneficial - Over a year, the rate at which the Best static facade configuration would perform sub-optimally

* This parameter will depend on the facade inclination, orientation and the location where it will be placed. Therefore, when designers give that parameter, implicitly they are also defining the geometrical and climatic conditions of the facade they are designing. Note: An illustration of DCA application: for a residential building in Almeria (Spain), for a south-oriented vertical opaque facade, DCA tool detects that the static opaque facade would behave in a suboptimal way at least 30% of the time over a whole year. High insulation of the envelope would be desirable at least 44% of the time, but on the other hand, heat dissipation would be preferable 28% of the year. Besides, the cladding with low solar absorptance would be beneficial 30% of the times, whereas a cladding with high solar absorptance would be preferable 42% of the year. Thus, as there is not a dominant thermal behaviour which is preferred during a whole year, the adaptive response of the cladding and of the insulation component would be suitable.

The subsequent step is to define a Reference Static Facade which will be the benchmark to improve, according to the legal requirements and the clients' needs. Reference Static Facade works as comparison benchmarks to calculate the potential improvements in the thermal energy demand when AOF are applied instead of mainstream opaque facades. To identify which is a good performing Reference Static Facade for each location and building use, the characteristic of the facade should be calculated at least according to the national regulations. For more ambitious design solutions, requirements established by specific Environmental Certifications can be useful when defining the Reference Static Facade.

The next step is to consider which are the responsive technologies that are available, which should not be based only in the current technology state of the art, but also on the understanding of the construction implications that have the integration of dynamic technologies and materials in facade systems. To do so, it is necessary to understand first in which way opaque facades can perform in an adaptive way. Such adaptiveness can be only obtained by integrating in the opaque facade systems, materials and technologies which are "able to vary the thermal behaviour repeatedly and reversibly over the time, under different boundary conditions" [81]. The systematic literature review of previous research works enabled the understanding of the construction and design implications that would have to build with these novel technologies, which were not always developed for the facade industry. In [77], these technologies are explored and analysed by separating them into (a) construction elements—a material manufactured with a specific geometry and configuration; (b) facade components—combination of elements; or (c) facade systems—combination of components and elements. This research identified facade elements with a kinetic behaviour, elements with adaptive thermal behaviour, dynamic components and facade systems. Then, they were analysed qualitatively to see if they were able to fulfil the facade system requirements (i.e., guaranteeing the appropriate hygrothermal and acoustic performance, hygienic and comfort requirements, as well as durability, safety and economical aspects). Accordingly, as summarized in Table 3, by using the qualitative approach of [77], main responsive technologies can be selected in this second step in order to get the dynamic thermal behaviour(s) which was/were detected as the most preferable one(s) at the first design step.

Table 3. Design support provided by Qualitative Analysis of Promising Materials and Technologies for the Design and Evaluation of Adaptive Opaque Facades [77].

Input	Design Support	Output
- Facade element with a kinetic behavior - Facade element with adaptive thermal behavior - Dynamic component - Facade systems.	- Qualitative Visual Analysis (when the material/dynamic technology was studied in the support document) - Methodological Approach to analyse qualitatively the technical information of novel smart materials/dynamic technologies	- From level I to VI, to which extend the analysed dynamic technology/material/AOF system fulfil the following facade requirements: • Hygrothermal performance • Hygienic requirements • Adaptive Facade performance • Durability • Acoustic requirements • Security requirements • Qualities influencing facade construction • Qualities influencing the economy of the facade.

Note: By way of illustration, thermochromics could contribute enhancing solar heat gains or to dissipate them depending on the external temperatures, as they change their solar absorptance when they reach a certain temperature. However, as the visual qualitative analysis points out, they do not provide the required thermal insulation and storage. Thus, they should be combined with other facade elements to build an AOF system.

The next stage is to take into consideration the aesthetical effects of the aforementioned pre-selected technologies and to define the possible AOF typologies resulting from the integration of those dynamic technologies with static facade materials. To understand the design implications of integrating the detected dynamic technologies (i.e., their appearance, dimensions or weight); in [78] there is a literature review with a more detailed focus on the design characteristics of novel Smart and Multifunctional Materials. The definition of the design properties of these materials and their meaningful physical properties enabled the assignation of possible new roles to Smart and

Multifunctional Materials. By using that information (which is exposed in Table 4), the AOF typologies are selected and initial AOF design option can be defined (i.e., definition of all the materials and facade elements composing the opaque facade system, as well as detailing the system graphically (sketches) and sizing each element).

Table 4. Design support provided by Smart and Multifunctional Materials and their Possible Application in Façade Systems [78].

Input	Design Support	Output for the Analysed Smart and Multifunctional Materials
- Material Family	- Definition of design potential and limitations - Analysis of the dynamic operation of Smart and Multifunctional Materials	- Proposal of possible innovative opaque facade integration (exterior cladding/intermediate layer/interior cladding/movable double skin) - Possible dynamic roles/Adaptive Facade Responses - Definition of type of autoreactive facade element (e.g., film, dyes, device, surface, actuator, etc.) - Available colours - Summary of meaningful physical properties

Note: For instance, thermochromic material family can allow AOF to have a new role: to change the temperature of the external cladding according to boundary conditions. Thermochromics can be integrated in facade elements as films, inks/pigments, powders, plastic pellets or dyes. The coatings integrating these smart materials have a wide colour availability: blue, grey, brown, ochre, red, and so on. The meaningful physical property when analyzing the adaptiveness of thermochromics in AOF is the adaptation range of their solar transmittance.

For the candidate AOF typologies, the resulting dynamic thermal behaviour should be conceptually outlined, in order to detect the effect that would have the selection and position of dynamic technologies in the multi-layered facade construction system. At this point, an iterative design process can be helpful when outlining the desired dynamic thermal behaviour, as it is related with the possible facade typologies and the position of dynamic effects might also affect the aesthetics of the AOF. To outline the resulting dynamic thermal behaviour, in [59] the main output of previous researchers was merged to explore and propose new adaptive opaque facade configurations. This consisted of a mapping which combines possible responsive technologies with other static building elements, based on the overall holistic adaptive thermal performance that designers are seeking. Even if the conceptual approach was exposed by proposing the possible application of advanced materials, the methodology can also be valid for any kind of responsive actuators. The output of this design stage, which is compiled in Table 5, is the selection of adaptive and static technologies and the definition of their position in the multi-layered facade construction system.

Table 5. Design support provided by Exploring the Potential of Smart and Multifunctional Materials in Adaptive Opaque Facade Systems [59].

Input	Design Support	Output
- Candidate Dynamic technologies for a multi-layered AOF - Candidate conventional Static building materials	- Definition of relevant physical properties when they are integrated in the exterior cladding/interior cladding - Outline of the physical property requirements of exterior cladding materials if designers aim to shift	- Possible combinations of dynamic and static facade technologies

for a multi-layer AOF	from thermal dissipation to convective insulation - Summary of the morphological requirements of the air cavity to shift from thermal dissipation to convective insulation - Methodological approach to map possible technology combination in such a way that ideal thermal behaviour is outlined

Note: Following the example of choosing thermochromics as candidate dynamic material, adaptive solar control facades result from the adequate combination of thermochromic-coated claddings with other facade components. When the facade aims to gain thermal energy from solar radiation, heat transfer needs to be as fast and effective as possible in the cladding, in such a way that it can be stored in the internal layer or transferred to the interior environment. Therefore, it would be suitable to have a thermochromic coating in a metallic cladding. Heat gained in the outer skin would be transferred to the internal layers when necessary, so that an Adaptive Insulation Component would be beneficial to block or allow heat exchange. The transmitted solar heat gain should be stored to release the thermal energy when necessary, for instance, thanks to a concrete wall which has a high thermal mass. Finally, this heat would be transferred to the interior environment through convection and radiation. When solar gains are detrimental to thermal comfort, the exterior cladding of the Adaptive Insulation Component would block the energy exchange.

The last two steps of the design process correspond to the simulation-based early-stage design approach methodology of Adaptive Opaque Facades, based on the approach proposed in [72]. The simulation of adaptive facades is a complicated task, as existing simulation tools were not originally developed for this purpose [82]. The followed simulation methodology facilitates the task for 15 possible AOF typologies which can have a common simulation strategy within EnergyPlus software. EnergyPlus can consider the different behaviour of Adaptive Opaque Facades by assigning more than one Construction to the Opaque Facades. By using the Energy Management System within EnergyPlus, designers can change the facade behaviour according to the boundary conditions. The simulation-based approach helps designers in defining the constructions and their behaviours based on the technologies that are integrated in their facades and in pointing out designers which sensors are needed. Moreover, it provides defined program scripts to control different technologies in a suitable way. This enables designers to quantify the performance of their AOF. The applied simulation strategy is able to consider the adaptive heat transfer behaviours which do not imply any mass exchange between indoor and outdoor environment, nor any latent heat storage mechanism. In the mentioned work, AOF with these characteristics were also classified in different typologies based on current construction techniques and integrated dynamic technologies. Furthermore, their complexity level was evaluated, which was defined by the integration of different heat transfer mechanisms and the control type (i.e., active or passive).

The final step of the design roadmap consists of quantifying the impact of different design decision and understanding in which way the thermal performance of proposed AOF improves the Reference Static Facade which was stablished as the benchmark (Table 6). The aforementioned simulation-based design method [72] can provide support in giving information about (i) how the performance of these facade typologies can be evaluated; (ii) how the performance of AOF typologies can be compared to choose the most promising one; (iii) how ineffective AOF typology options can be removed when they do not improve the static performance reference, and (iv) how to understand the thermal performance impact when modifying AOF design parameters. Through the simulation-based design methodology, designers can decide if the achieved benefits in the thermal performance of the building deserve the additional complexity that implies the integration of dynamic technologies. If the obtained results do not fulfil the design objective, the researchers should re-start the process from the selection of the facade typology.

Table 6. Design support provided by Dynamic thermal performance simulation based on current technological state for assisting on the design of Adaptive Opaque Facades [72].

Input	Design Support	Output
- Selected combinations of dynamic and static facade technologies - Adaptation Range of Dynamic technologies /materials - Physical characteristics of selected materials - Control of dynamic technologies /materials (needed sensors and placement) - Reference simulation room Weather file	- Definition of the complexity degree of the resulting facade technology - Simulation strategy to model in EnergyPlus one of the 15 AOF typologies which include (i) variation of solar absorptance of the cladding, (ii) variation of the convective heat transfer of air cavities and (iii) adaptive insulation strategies, and the combinations of them. - Control scripts to run out dynamic thermal simulations in EnergyPlus for 15 different AOF typologies. - Methodological approach to evaluate promising design solutions for Adaptive Opaque Facades (AOF) on the basis of whole building performance indicators, considering design variables such as build-up and range of variation of physical properties, and control complexity of the technological solution.	- Quantification of annual Heating and Cooling Energy use for the selected AOF typology. - Quantification of the Total Delivered Energy - Quantification of annual Adaptation Cycles - Relative thermal improvement respect the Static Performance Reference.

Note: To conclude the illustration of the design of a heavyweight AOF which includes a thermochromic coating, a dynamic thermal performance simulation needs to be carried out. As explained in [72], thermochromic coatings activated when reaching 30–31 °C proved to have worse performance compared to the Reference Static Facade in residential buildings located in temperate coastal locations. Using the iterative design process, designers could learn that actively controlled claddings which are able to change the solar absorptance of AOF improved the thermal performance, due to a more complex and adequate control strategy.

3.2. Validation of the Roadmap Usability

This section presents the usability validation of the design roadmap. The results of the workshop were used in this regard. First, the suitability of the selected climates and building use for the workshop is demonstrated. Then, the workshop results are presented (that is, the facades students designed and the thermal performance they calculated). The last part of this section exposes the answers students provided to a qualitative survey at the end of the workshop, which aimed to demonstrate that the roadmap serves beyond the exercise students did.

3.2.1. Verification of Selected Case Studies: the Potential of AOF in Selected Temperate Coastal Locations and Residential Buildings

The climates used in the workshop as case studies were previously checked by the authors in order to verify that AOF design would offer an opportunity to improve the Static Reference Facade benchmark. It should be remembered that the performance of Adaptive Facades is mostly determined by local weather conditions and internal heat gains. That is why DCA was used to check that selected locations for the workshop were the suitable ones [76]. Moreover, similar climates were proved to be promising in previous research works [72,76]. Accordingly, the chosen climates were

Istanbul (Csa), Buenos Aires (Cfa), Los Angeles (Csb) and Valencia (Bsk) according to Koppen classification [83]. The DCA tool detected that for residential buildings, south and west orientations were the most promising places for the AOF installation in the North Hemisphere locations, and north and west for Buenos Aires. DCA also signalled that adapting the thermal heat transfer was the most promising adaptive thermal behaviour in all locations. According to the DCA, the variation of the solar absorptance had also a significant potential in all locations. In the same vein, the simulation-based design approach proved that some AOF typologies could improve the benchmark. In particular, the most promising facade typology for all the proposed climates was an off-site wall with no air cavity which had an actively controlled kinetic cladding, which was also able to vary the solar absorptance of the facade, and which integrated an Adaptive Insulation component. To a fewer extent, an off-site wall which integrated an Adaptive Insulation component could also improve the benchmark.

3.2.2. Workshop Results: AOF Designs and Obtained Thermal Performance

Workshop participants were 20 architects and one construction manager. Their education background in architecture was notable in the results, as in general, they were all able to visualize somehow the design and appearance of Adaptive Opaque Facades. Six groups out of seven provided original sketches of their designs in the final presentation. Obtained results are summarized in Table 7 and it shows that 2 groups out of 7 designed and quantified successfully an AOF design option. All the groups reached the last design step -the evaluation of the thermal performance- and were able to run somehow AOF simulations. Group 3 was the one capable of meeting better all the requirements of the proposed task. They first detected through the DCA employment that in Buenos Aires, a North facade with a 34° inclinations from the vertical axis was a promising placement for an AOF which was capable of varying the solar absorptance (SA) of the cladding and the thermal Resistance of the opaque component (R). Thus, they defined a graphical sketch of a facade system which was composed of a kinetic cladding capable of rotating and changing the exposed material. The cladding was composed by two metal sheets and it had a metal with low SA on one side and another metal layer on the other side, with high SA. The AOF also integrated an adaptive insulation component, a concrete layer and a mortar finishing in the interior layer. The students of this group were able to follow the simulation-based design method and they quantified the energy reduction respect the Reference Static Facade. They got a reduction of 11.30% in heating energy use and a 5.6% in cooling energy use.

Table 7. Workshop results.

	DCA Employment	Benchmark Definition	Definition of Facade Materials and Elements	Graphical Sketches of the Proposal	Simulation Results	AOF Better than the Static Benchmark	They Followed the Workflow of the Roadmap
Group 1 Istanbul	(1) South Facade with 159° angle (2) Decision on AOFR missing *	U = 0.20 W/m²K WWR = 15% SA = 0.96 *	Ceramic tile (1.95 cm) + ventilated air cavity (10 cm) + plaster (1.25 cm) + Dynamic Insulation (15 cm) + Brick (10 cm)	Yes, original	Yes	Yes, 8% reduction in cooling energy use	Yes
Group 2 Istanbul	(1) South Facade with 65° angle (2) AOFR = Dynamic R + Dynamic SA	U = 0.29 W/m²K WWR = 21% SA = 0.6	Facade actively changing the reflectance of a cladding in a facade system with no air cavity and a dynamic insulation component *	Yes, but copied from the references *	Yes *	Yes, 1.5% reduction in heating and cooling energy use *	Yes
Group 3 Buenos Aires	(1) North, 34° Inclination (2) AOFR = Dynamic R + Dynamic SA	U = 0.27 W/m²K WWR = 9% * SA = 0.6 *	Metal cladding with low SA (0.03 m) + Metal cladding with high SA (0.03 m), Adaptive Insulation (0.17 m) + Concrete (0.01 m) + Mortar (0.013)	Yes, original	Yes	Yes, 11.30% reduction in heating 4nergy use and 5.60% reduction in cooling energy use	Yes
Group 4 Buenos Aires	(1) South Facade	U = 0.18 W/m²K * WWR = 15% SA = 0.96	Movable metal panel + air cavity + EPS Foam insulation + brick + plaster *	Yes, original	Yes	Yes, 0.8% reduction in cooling energy use	Not clear *
Group 5 Los Ángeles	Missing *	U = 0.37 W/m²K * WWR = 15% SA = 0.6	Thermochromic cladding + bi-directional thermodiode insulation + concrete wall + plaster *	Yes, original	Yes	Missing *	Not clear *
Group 6 Los Ángeles	(1) South Facade (2) AOFR Heat Dissipation + Heat Gain	Missing *	Metal cladding + Dynamic Insulation (Deployable Thermal Insulation, Mineral Wool) *, Brick	Yes, original	Yes	Yes, 26% reduction in heating energy use and 51% reduction in cooling energy use	Yes
Group 7 Valencia	(1) Missing * (2) AOFR Dynamic R + Dynamic SA	Missing *	Brown thermochromic paint + Dynamic Insulation + Concrete	Yes, original	Yes	Yes, 0.98% reduction in heating and cooling energy use *	Not clear *

When students did not carry out the design task in a suitable way, or when students obtained incorrect design answers *.

By examining the results, it can be concluded that half of the students could obtain reasonable AOF designs at different design stages, which enabled them to propose a well-designed AOF. Moreover, these students correspond to the ones who followed the chronological order proposed by the design roadmap. Nevertheless, the short duration of the workshop impeded students in improving the first AOF design parameters as proposed in [72], which would explain the low thermal performance improvement respect the static benchmark.

3.2.3. Qualitative Feedback Results

As explained in Section 2.2, students answered a qualitative survey after the workshop completion. Figure 5 summarizes their feedback regarding the correctness of each design step which constructs the roadmap. The overall response to this question was positive regarding the provided importance of the information in order to decide. Only few students were more discerning about the high importance that detecting Facade Typologies and considering the aesthetical effects had in their design process. The majority of students considered it important to define properly the benchmark during the design process. They also answered to an open question which aimed to detect if any additional key point or consideration was missing in the roadmap. Two students reported the need to include an additional key point about the economic impact of design decisions. Another one pointed out the importance of considering local resources as part of the design process. One respondent signalled the necessity to explain more clearly the why of each design step.

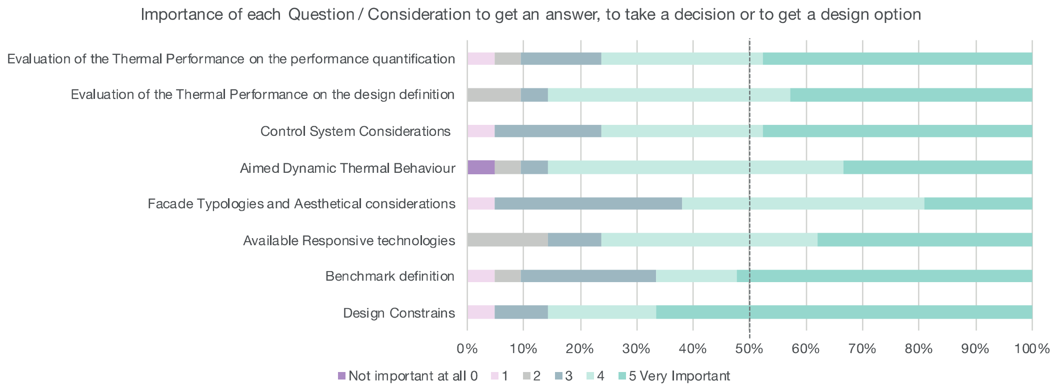


Figure 5. Qualitative feedback results regarding the importance of each question or consideration regarding the design roadmap.

The survey also aimed to verify if the methods proposed in the roadmap were applied within acceptable limitations and if they were useful during the design process. Figure 6 summarizes the qualitative information obtained. More than 40% of participants reported that the provided additional material—which is summarized in Table 1—was the most used source during each design step. Teachers' explanations—who were also the authors of the literature references in Table 1—were also detected as a greatly used source. Their assistance was especially useful for the benchmark definition and for the design steps corresponding to the dynamic simulations and thermal evaluation. The use of the internet at each design step was not meaningful. They only used the internet when they were considering the design constrains, the aesthetic considerations and, to a lesser extent, the available responsive technologies, aimed thermal behaviour and control system considerations. Sometimes, they also got valuable help from other students, as it happened for the simulation workflow, benchmark definition and design constraint.

When asked about the completeness of the provided materials, two students missed more demonstrative and visual examples of each facade typology. Another student reported the need to explain better how to differentiate the adaptive behaviour in different time scales, such as daytime and nighttime, as it would help to improve the design. All in all, 11 students out of 21 agreed that the provided support materials were complete.

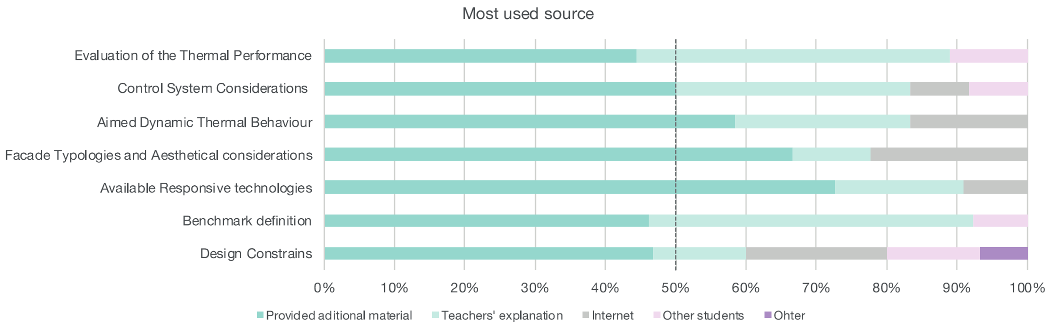


Figure 6. Qualitative feedback results which show which was the most used source when making design decisions.

The purpose of the last part of the survey was to evaluate the roadmap's clarity and usability. Figure 7 illustrates the feedback with regard to the complexity of the design workflow and the methods which construct it. The use of dynamic climate analysis seemed to be the simplest one among the design steps. More than half of students could somehow understand by using this tool which thermal behaviour was the most suitable one and said that they were able to check appropriately the potential of different facade orientations and inclinations. However, about 30% of students found DCA complex to use. Students were less confident about the way they used the provided support material in other design steps. It was especially difficult to carry out dynamic simulations and they had some problems in understanding the results they obtained.

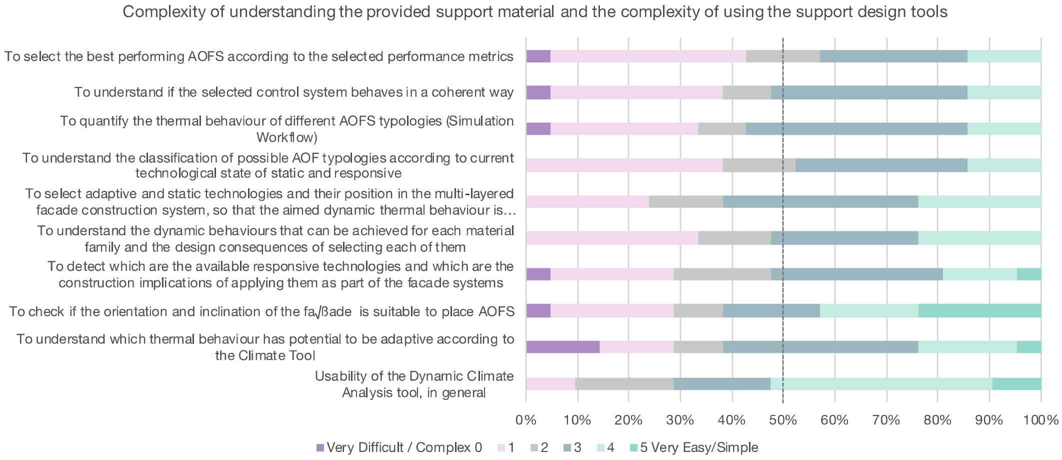


Figure 7. Qualitative feedback results about the complexity of the provided support-information.

The complexity of the design steps also has an impact on the general usability of the proposed design method (Figure 8). Most of the students appreciated the consistency of the design roadmap and confirmed that they would use the method proposed by the design roadmap if they had to consider the application of an AOF. However, the majority admitted that they did not feel confident during the design process, as it was difficult to follow the methodology. Over 25% of those surveyed reported that they would need help to follow again the design workflow proposed in the roadmap.

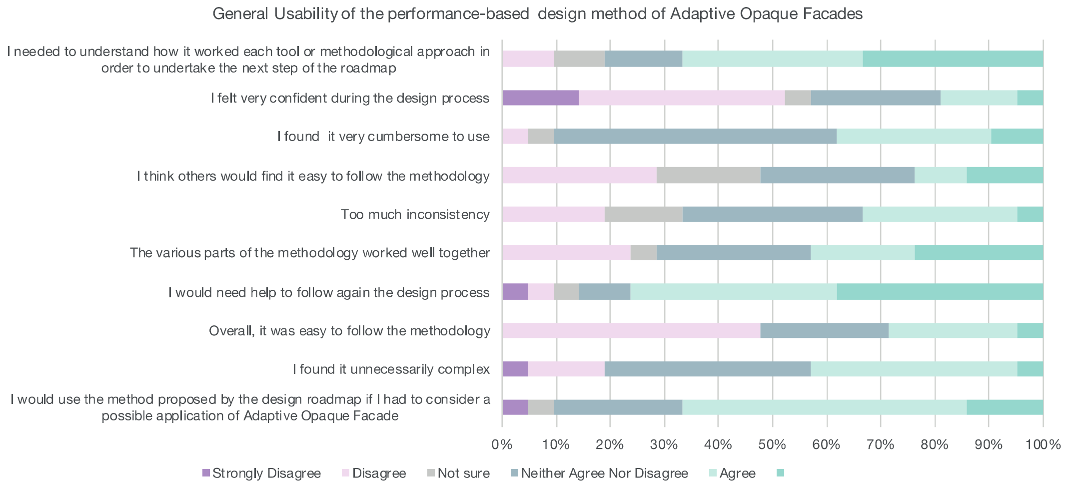


Figure 8. Qualitative feedback results about the usability of the design roadmap.

4. Discussion

The results of the roadmap development and its applicability showed that the design of Adaptive Opaque Facades is complicated, but architects and facade engineers now have enough information to define their characteristics at least at early design stages. Some students could successfully design an AOF and evaluate its thermal performance. The qualitative feedback revealed that students found the workshop task difficult to follow and that would partially explain why they did not feel confident with the thermal performance results they obtained. This issue would have been potentially solved by having more time. As the workshop only lasted three days, they were not able to analyse thoroughly their results, nor to improve their proposals by modifying some design parameters.

The lack of Adaptive Opaque Facade built examples would also partially explain the lack of confidence and understanding that students stated in the qualitative survey. Architectural design process is highly influenced by historical and local references. In design studio, the appropriateness of the proposed design is often evaluated according to the correct reference selection, which serves as a model to choose good design strategies. For instance, one of the students remarked in the survey that they needed more visual examples to understand the possible facade typologies and technological options (even if the lectures contained several sketches and drawings illustrating them graphically). This is a great limitation when proposing innovative designs or the integration of novel technologies, as these examples hardly exist. Having more physical prototypes and experimental assessments would serve to build up confidence in designers. Besides, it could be useful for architects to have more training in uncertainty analysis methods to evaluate the robustness of different design decisions under different conditions, such as weather or occupant behaviour.

Students made interesting remarks during the workshop about the necessity of including some economic aspects in the design process. However, it is questionable if this design concern really fits in the scope of the roadmap. This was thought for the construction definition of innovative Adaptive Opaque Facades at early design stages, prior to first prototyping or mock-up testing procedures. Hence, the ultimate valorisation of the economic feasibility in the design proposals should be done for those designs which will be integrated in full-scale buildings. Still, more technological maturity is needed before being able to evaluate this aspect. However, future works in next design steps—subsequent to early-stage design decisions—could consider the availability of primary material and production systems when considering economic issues. The characteristics determining their possible integration in a circular economy, as the ones presented by Battisti et al. and Al-Saggaf et al. [26,27], may shed some light on life cycle, cost and feasibility questions.

For some AOF applications, the support documents assisting during certain key points and design consideration could be extended. In a paper published after the end of the workshop, Andrade et al. [79] proposed some criteria to assist on the application of auto-responsive technologies in the renovation of opaque facades. This information would enlarge the one proposed in this work on the "Façade Typology and Aesthetics" key point, as they exposed the criteria of aesthetic change of existing facades, they detected the area of intervention in different facades, highlighted the possible additional space need for the integration of some technologies, as well as possible demolition needs. Similarly, the upcoming publication of Soudian et al. could be helpful in including in the design roadmap some initial pre-design considerations about the life cycle, use/operation and end of life, by taking into account the metrics they identified [22]. Besides, the roadmap proposed in [23] explains how to integrate adaptive facades in zero emission neighbourhoods, which will be of key importance to apply AOF correctly in the build environment when they become a feasible solution. The work of Taveres-Cachat does so by detecting the requirements associates to the interaction between buildings. Thus, future work could identify which design steps need to take this issue into account to inform and assist designers in this regard.

During the workshop, residential buildings and temperate coastal locations were used as case-study. The results confirmed the potential of Adaptive Opaque Facades application for the aforementioned boundary conditions. The outputs of this workshop and the results of other research works found in literature suggest that it would be possible to develop some design guidelines which simplify the design process, as similar building uses and climates seem to point out to same promising facade configurations. Further research could develop those guidelines by carrying out a large number of building simulations. Big-data analysis could help to detect best facade configuration for each building use, similar space configurations, facade features and climate type. These design guidelines could be intermediate steps between the dynamic climate analysis and the simulation-based design methods. These guidelines would add information to designers, but to finetune the design of the Adaptive Opaque Facades, the simulation-based design method would still be needed.

5. Conclusions

This paper presented the development and validation of a roadmap to assist the performance-based design process of Adaptive Opaque Facades, in such a way that the thermal performance is considered appropriately in the early-stage decision-making process. The aim was to support the early-stage design process of Adaptive Opaque Facades by detecting and organizing the methods and tools which were suited for their particular design considerations. The roadmap proposes a design workflow and consists of seven steps, each of which is supported by a respective tool:

1. Design constrains: Dynamic climate analysis tool enabled the detection of the facade orientation(s) that offered suitable conditions to place an AOF and identified preferred adaptive responses. In this first step, it was also possible to test by using DCA tool if there was any facade inclination which improved the AOF performance.
2. Benchmark definition: based on the legal requirements and the client's requirement, it was possible to define the Reference Static Facade, which served as a benchmark to improve.
3. Available responsive technologies: the qualitative analysis of promising materials and technologies assisted in identifying to which extend these technologies could contribute in the fulfilment of the facade requirements.
4. Facade typology and aesthetics: based on the literature review it was possible to select AOF typologies and initial AOF design options were defined (i.e., selection of all the materials and facade elements composing the opaque facade system, graphical detailing and sizing of each element).
5. Desire Dynamic Thermal Behaviour: by following the methodology, designers could select adaptive and static technologies and they defined their position in the multi-layer facade construction system.
6. Control System: the simulation-based design method supported designers by giving them the Control scripts to run out dynamic thermal simulations in EnergyPlus for 15 different AOF typologies.

7. Evaluation of the thermal performance: Through a simulation-based design methodology, designers were able to quantify the thermal performance of the building and, accordingly, they evaluated if the additional complexity that would imply the integration of dynamic technologies was deserved or not.

The roadmap brings a new and complete performance-based design workflow for Adaptive Opaque Facades, which enables their complex construction definition at early-design stages, prior to prototyping or mock-up testing procedures and makes the quantification of AOF performance possible. The workshop served to validate the consistency and completeness of the roadmap and demonstrated that it simplifies the task of designing AOF, as some students could successfully design and define the early-stage design characteristics of an AOF in three days. As a final remark, by following this roadmap, designers and architects will be able to design different Adaptive Opaque Facades and boost their real construction in buildings that take advantage of climate conditions to be more comfortable and low energy consuming.

Future studies could evaluate how to include initial considerations about Life Cycle Analysis and Life Cycle Cost in the Adaptive Opaque Facade design roadmap. Besides, further works should illustrate how the physical mock-ups of adaptive facades can enhance the design proposals. Experimental assessment of these prototypes will also be useful to optimize some of the design methods presented in this roadmap and will enable creating specific framework to measure the components′ potential heat transfer based on climatic conditions. Moreover, constructed design examples would offer visual examples of Adaptive Opaque Facades to designers, which are crucial to encourage architects and facade engineers to apply innovative building envelopes.

Author Contributions: Conceptualization, methodology, validation, investigation, data curation, visualization writing—original draft preparation: M.J.; methodology, formal analysis, writing—review and editing: T.K. and A.M.-B.; supervision, project administration: T.G.-A. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is part of the PhD research project titled "Adaptive Opaque Facades: a Performance Based Design Method", funded by Asociación de Amigos de la Universidad de Navarra and Banco Santander.

Acknowledgments: The authors would like to acknowledge the commitment and interest of students participating in the workshop "Performance-based Design and Assessment of Adaptive Facades". Similarly, we gratefully acknowledge Fabio Favoino, Roel Loonen and Francesco Isaia for their lectures, workshop organization and students' assistance. All three were essential for the success of this international seminar. We would also like to thank the University of Navarra and the Master in Environmental Design and Building Management for letting us organizing this workshop. Last but not least, we wish to appreciate COST Action TU1403 "Adaptive Façade Network" for providing an excellent network.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Workshop Task

Design [1] and quantify [2] the performance of at least one Adaptive Opaque Facade System for the given representative building space [3], according to the climate and urban context [4] that was selected for your group. The results will be exposed in 5 min presentations [5] on Friday 28th February at 17:30.

What is meant by…

[1] Design: Define all the materials and facade elements composing the opaque facade system and define the system graphically (sketches) naming and sizing each element. Window-to-wall ratio and the design of the transparent part of the envelope will be up to each group.

[2] Quantify: Select a performing reference static facade system of which the U value fits with the guide values of Table a-Annex E [52] and establish a benchmark to improve ±30% of the guide value. Choose the performance metrics and calculate the improvement with respect to the reference static facade system.

[3] Building space: the interior dimension is 4.5 × 4 × 2.5 m. The building use will be residential. The number of exposed facades, their inclination, as well as their orientations will be decided by each

group. At least one of the designed facade system needs to be Adaptive Opaque Facade. The number of windows and their dimensions are also up to each group.

[4] Climate and urban context per group (Table A1)

Table A1. Climate and Urban context per group.

	Location	HDD (16 °C)	CDD (24 °C)	Urban Context
Group 1	Istanbul	1452.9	123.67	Historical centre
Group 2				Financial centre
Group 3	Buenos Aires	882.39	154.71	Financial centre
Group 4				Historical centre
Group 5	Los Angeles	387.42	9.06	Financial centre
Group 6				Historical centre
Group 7	Valencia	791.10	212.16	Historical centre

[5] Presentation: the presentation will include a slide explaining the design workflow order that was followed to define the definitive Adaptive Opaque Facade System, including the iterations that were needed.

Appendix B. Set of Questions

1. Please, indicate your background (Architect, Civil Engineer, etc.)
2. Do you have professional experience as an architect?
   - Yes, more than 5 years
   - Yes, more than 3 years
   - Yes, more than 1 year
   - No
3. Importance of each Question/Consideration to get an answer, to make a decision or to get a design option.

	Not Important at all	1	2	3	4	Very Important
Design constrains: contextual and architectural considerations to understand the possible application of Adaptive Opaque Facades and its placement	☐	☐	☐	☐	☐	☐
Benchmark definition: legal and client's requirements to get a static reference facade	☐	☐	☐	☐	☐	☐
Available Responsive technologies to define the composition of the Adaptive Opaque Facade that is being designed	☐	☐	☐	☐	☐	☐
Facade typology and aesthetics considerations to define the composition of the Adaptive Opaque Facade that is being designed	☐	☐	☐	☐	☐	☐
Aimed Dynamic Thermal Behaviour to define the composition of the Adaptive Opaque Facade that is being designed	☐	☐	☐	☐	☐	☐
Control System considerations to define properly these facade elements (needed sensors, actuators, program script, etc.)	☐	☐	☐	☐	☐	☐
Defined considerations for the evaluation of the thermal performance to define properly the design parameters of Adaptive Opaque Facades	☐	☐	☐	☐	☐	☐

Defined considerations for the evaluation of the thermal performance to quantify properly the designed Adaptive Opaque Facades	☐	☐	☐	☐	☐	☐

4. Any additional key points and consideration missing and/or suggested?
5. For each step of the roadmap, how did you get support? (Rate them from most used source (5) to the less used one (1). If one of them did not provide you with support, rate it (0).

	Provided Additional Material	**Teachers' Explanation during the Practical Workshop**	**Internet**	**Other Students**	**Other**
Design Constrains	☐	☐	☐	☐	☐
Benchmark definition	☐	☐	☐	☐	☐
Available Responsive technologies	☐	☐	☐	☐	☐
Facade Typology and Aesthetics	☐	☐	☐	☐	☐
Aimed Dynamic Thermal Behaviour	☐	☐	☐	☐	☐
Control System	☐	☐	☐	☐	☐
Evaluation of the Thermal Performance	☐	☐	☐	☐	☐

6. Was the provided material complete for each step of the roadmap? If not, what did you miss?
7. Rate the complexity of understanding the provided support material and the complexity of using the support design tools:

	Very Difficult/Complex					**Very Easy/Simple**
	0	**1**	**2**	**3**	**4**	**5**
Dynamic Climate Analysis tool [76]						
Usability of the Dynamic Climate Analysis tool, in general	☐	☐	☐	☐	☐	☐
To understand which thermal behaviour has potential to be adaptive according to the climate Tool	☐	☐	☐	☐	☐	☐
To check if the orientation and inclination of the facade is suitable to place AOF	☐	☐	☐	☐	☐	☐

	Very Difficult/Complex 0	**1**	**2**	**3**	**4**	**Very Easy/Simple 5**
Qualitative analysis of promising materials and technologies for the design and evaluation of Climate Adaptive Opaque Facades [77]						
To detect which are the available responsive technologies and which are the construction implications of applying them as part of the facade systems	☐	☐	☐	☐	☐	☐

	Very Difficult/Complex 0	**1**	**2**	**3**	**4**	**Very Easy/Simple 5**
Smart and Multifunctional Materials and their Possible Application in Facade Systems [78]						
To understand the dynamic behaviours that can be achieved for each material family and the design consequences of selecting each of them.	☐	☐	☐	☐	☐	☐

	Very Difficult/Complex 0	**1**	**2**	**3**	**4**	**Very Easy/Simple 5**
Exploring the potential of Smart and Multifunctional Materials in Adaptive Opaque Facade Systems [59]						
To select adaptive and static technologies and their position in the multi-layered facade construction system, so that the aimed dynamic thermal behaviour is obtained.	☐	☐	☐	☐	☐	☐

	Very Difficult/Complex 0	**1**	**2**	**3**	**4**	**Very Easy/Simple 5**
Dynamic thermal performance simulation based on current technological state for assisting on the design of Adaptive Opaque Facades [72]						
To understand the classification of possible AOF typologies according to current technological state of static and responsive technologies	☐	☐	☐	☐	☐	☐
To quantify the thermal behaviour of different AOFS typologies (Simulation Workflow)	☐	☐	☐	☐	☐	☐
To understand if the selected control system behaves in a coherent way	☐	☐	☐	☐	☐	☐
To select the best performing AOFS according to the selected performance metrics	☐	☐	☐	☐	☐	☐

8. General Usability of the performance-based design method of Adaptive Opaque Facades. Please, check a box for each statement to show how much you agree or disagree with it:

	Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree	Not Sure
I would use the method proposed by the design roadmap if I had to consider a possible application of Adaptive Opaque Facade	☐	☐	☐	☐	☐	☐
I found it unnecessarily complex	☐	☐	☐	☐	☐	☐
Overall, it was easy to follow the methodology	☐	☐	☐	☐	☐	☐
I would need help to follow again the design process.	☐	☐	☐	☐	☐	☐
The various parts of the methodology worked well together	☐	☐	☐	☐	☐	☐
Too much inconsistency	☐	☐	☐	☐	☐	☐
I think others would find it easy to follow the methodology	☐	☐	☐	☐	☐	☐
I found it very cumbersome to use	☐	☐	☐	☐	☐	☐
I felt very confident during the design process	☐	☐	☐	☐	☐	☐
I needed to understand how each tool or methodological approach worked in order to undertake the next step of the roadmap	☐	☐	☐	☐	☐	☐

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