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Solar Cooling Integrated Façades: Key perceived enabling factors and prospects of future applications

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ABSTRACT

Solar cooling integrated façades (SCIFs) have the potential to reduce primary energy consumption for space cooling. Identifying key enabling factors in the context of technical and product (T&P), financial (F), as well as process and stakeholder (P&S) related aspects represent an important step providing relevant knowledge for implementing solutions supporting the widespread application. This study aims to identify main factors enabling the widespread integration of SCTs in façades from the point of view of various professionals. An interview guide was designed to tackle main aspects to be considered for supporting the widespread application. Different criteria were considered to select the interviewees during the data collection, such as participants who worked on the application or façade integration of solar/SCTs in buildings. The findings obtained from a total of 23 interviews revealed that the most frequently mentioned factors are product performance and efficiency, facilitating the delivery of product information to architects and clients, aesthetical acceptability, multidisciplinary teamwork, and ability to customize products. The factors were mapped in the context of façade design and construction processes to establish a matrix for implementing solutions in product development. Majority of the factors were linked to the design phase according interviewees' perceptions. The results also indicated that newly built office buildings have been perceived to be one of the most relevant types of buildings to be considered for such technologies. The identified enabling factors and prospects of future applications of solar cooling integrated facades (SCIFs) contribute to expand the boundaries of knowledge in the field of building product development.

List of abbreviations

F	Financial
GHG	Greenhouse gas
P&S	Process and stakeholder
PV	Photovoltaic
PVT	Photovoltaic-thermal (PVT)
SCIFs	Solar cooling integrated facades
SCTs	Solar cooling technologies
STC	Solar Thermal Collector

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T&P	Technical and product
TE	Thermoelectric

1. Introduction

The global need for cooling is expected to increase in the coming future due to climate change [1,2], in addition to other factors comprising the population and economic growth with the subsequent increase in the quality of life, and the affordability of air-conditioning units [2,3]. Furthermore, it was estimated that the global energy demand for the building space cooling may increase by 50% in 2030 [4,5]. The increase in the use of conventional mechanical cooling systems can increase greenhouse gas (GHG) emissions, due to their dependency on electricity generated in power plants [2]. Hence, this necessitates the use of cooling systems that can meet the expected increase in the demand for space cooling, while avoiding systems contributing increase (GHG) emissions.

The production of cooling effect through solar radiation is one of the strategies to be considered for reducing challenges related to the increase in the required cooling demands in the built environment. The potential advantages of solar cooling technologies (SCTs) include saving primary energy and reducing peak demand for energy cost saving [6]. The technologies can be in a form of producing hot water through Solar Thermal Collectors (STC) or producing electricity through Photovoltaic (PV) panels [7]. This represents two principal pathways for energy conversion to be used to produce cooling effect from solar radiation, namely thermally driven processes or electrically driven processes [7–13]. Building façades provide opportunities to integrate SCTs, as they provide external surfaces exposed to solar radiation, while also impacting indoor thermal comfort [14]. The knowledge development and abundance associated with different scientific disciplines has enabled façade engineering to advance the building envelope industry [15]. Building façades are moving toward being multifunctional components that are actively involved in the building energy system through integrating services that contribute to energy savings and building occupants' comfort [16–18]. When having an insight into the consideration of solar cooling technologies, solar cooling integrated façades (SCIF) were previously defined as "*façade systems which comprise all necessary equipment to self-sufficiently provide solar driven cooling to a particular indoor environment*", which indicated that the necessary equipment needed at least for cooling generation and distribution should be integrated by façade systems [8].

It should be noted that the widespread application of such defined façade concepts in the construction industry is far from what it could be due to different forms of challenges. Hamida et al. [19] identified and categorized these challenges, and proposed three main aspects to be tackled to enable the widespread application of SCIFs. The aspects include Technical& Product(T&P)-related, Financial (F)-related, and Process& Stakeholder (P&S)-related (Fig. 1). Such proposed aspects demonstrate that fact that many social phenomena are associated with various bodies of knowledge belonging to a set of different disciplines [20]. For instance, considering the T&P-dimension, products tend to have a particular scope of certain features and functions [21]. Facades as building products are intended to have multiple functions during the use phase, including the insulation with respect to heat, cold, and noises [22]. Regarding the integration of SCTs into façades, various technical attributes have been considered to affect the product applicability of SCIFs, including sizes and number of required components [23]. Accordingly, investigating key factors enabling the product applicability within such aspects can have a vital role in future developments of SCIFs. Having an insight to the F-related aspects, cost is one of the most common barriers affect the widespread application of such technologies [24]. Consequently, investigating the key factors enabling the achievement of cost-effective products through lowering the requirement related the upfront capital can support the

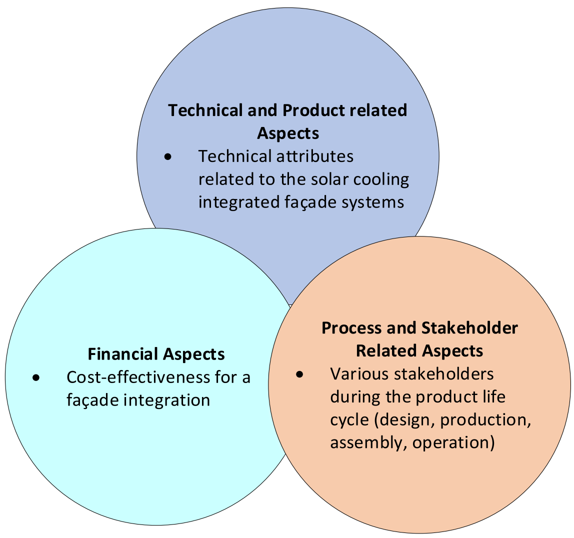

Fig. 1. Proposed aspects to be tackled for supporting the application of SCIFs [19].

market penetration [25]. For P&S dimension, there are various stakeholders that are involved in the product life-cycle (design, production, assembly, and operation phases) [26]. Accordingly, considering this dimension requires focusing on identifying factors that enable stakeholders to adopt such technologies through considering key relevant aspects, such as the knowledge and experience [27].

Based on the previous paragraph, it is obvious that tackling proposed aspects requires grounding them into key factors enabling the widespread application within the context of these different disciplines. The identification of such factors can help in providing a relevant knowledge needed for investigating the future product applicability in the construction industry. Consequently, in order to deal with such multiple bodies of knowledge related to the proposed aspects, a multidisciplinary research approach and methods is required. Qualitative research methods provide relevant tools needed to understand phenomena linked to different disciplines [20]. Hence, this study focuses on grounding the aspects qualitatively into key enabling factors. This paper aims to identify key perceived enabling factors and prospects of future applications related to the widespread application of SCIFs, which can provide relevant knowledge needed for future product development. With respect to that, the main research question to be explored in this study corresponds to:

- *What are the key perceived enabling factors and prospects of future applications of façade products integrating SCTs?*

In order to answer this research question, this study involved 23 qualitative interviews with various professionals who can provide can provide relevant information related to the key perceived factors within the context of different aspects. The research approach and methods section presents all aspects related to the design of interview guide, criteria for selecting interviewees, and the analysis of collected data. Following which sections 3 and 4 illustrate the interviews results and discussion, respectively. Finally, the conclusion section discuss the findings, limitations, and future research scope.

Such outcomes can facilitate establishing a matrix for implementing the solutions in product development. Such established matrix of enabling factors obtained from this exploratory study provide information that can be considered and investigated in future works related to the to the development of frameworks supporting the widespread application of SCIFs. Such frameworks can consider the applicability of particular SCTs in particular contexts.

2. Research approach and methods

To identify the key factors that can enable the widespread integration of SCTs in façades, this study adopted the research approach and methods indicated in Fig. 2:

2.1. Design of interview guide

In order to ground the aspects to key enabling factors, qualitative interviews with professionals were considered in order to reach an in-depth understanding of perceptions and insights of experts on such particular topic [28,29]. Such research approach can help in capturing the voices of experts through a one-to-one discussion between the interviewer and interviewee on a specific topic [29,30]. It

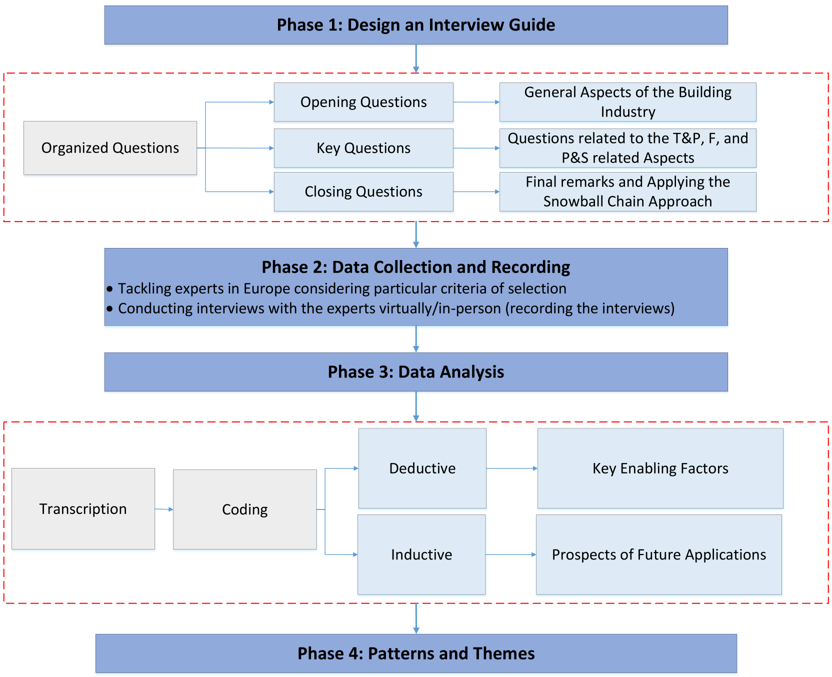

Fig. 2. Research approach and methods.

should be noted that it is essential to identify and screen out the phenomena to be examined from the environment of study in order for a qualitative research to reach a yielded conclusion [31]. Accordingly, the core of the qualitative interviews circled around the three identified groups of aspects. To collect the data appropriately, it is essential to have an organized interview guide that includes an introductory part, opening questions, key questions, and closing question [30,32]. The opening and closing questions are intended to collect supplementary information that include the perception of participants about general aspects, such as opinions about type of buildings considered to be relevant for supporting widespread application of façade products integrating such technologies. Apart from the opening and closing questions, the key questions, representing the core of the qualitative interviews, are intended to cover the three aspects. The design of the interview guide was prepared and revised among the research team members and colleagues in the research group, and was tested with the following two experts:

interview guide was prepared and revised among the research team members and colleagues in the research group, and was tested with the following two experts:

- A director of a research and consultancy firm that focuses indoor environment in buildings.
- A professor in field of climate responsive design and building technologies.

The purpose of testing the interview guide is to check time it takes to complete the interview as well as the clarity of questions, words, and sentences. It also involved checking the logical order of questions [30]. Based on these two testing interviews, the questions were revised as indicated in Appendix A.

2.2. Data collection

The qualitative interviews in this study tackled practitioners and applied researchers that are experts in the European building industry. The interviews were based on a purposive, non-probabilistic, sampling [29,31]. This is due to the fact that this exploratory study focuses on investigating the key factors enabling the widespread application of SCIFs in the context of the three main aspects considering a particular group of experts. Hence, it is essential to have predetermined criteria to select the participants [33,34]. Accordingly, considering the technical and product (T&P) related aspects, it is essential to have practitioners and applied researchers who are experts in the application or façade integration of solar or solar cooling technologies. For the financial (F) as well as process and stakeholder (P&S) related aspects, broadening the sample through involving practical experience from the building industry by involving experts in the facade design and construction is important. Consequently, the main criteria considered for selecting interviewees include that experts should achieve one or more of the following conditions to ensure their competence:

- Involvement in the façade design and construction industry (design, production, assembly, and/or operation/maintenance).
- Involvement in projects related to the application or façade integration of solar/solar cooling technologies.
- Involvement in the research& development (R&D) or applied research in relevant fields, such as multi-functional façades, including prototyping façade products integrating solar/solar cooling technologies or other relevant subject.

The snowball chain approach was also applied in this study at which participants are allowed to propose other potential interviewees who are relevant to participate in this study [35,36]. This approach has been adopted in previous studies in order to reach interviewees having a relevant experience [29,34]. Taking into account all of the previously mentioned criteria, the finalized number of interviews to be conducted was considered to be between 20 and 30 in order to ensure a relevant number of participants as it has been indicated by Refs. [32,35]. The interviews were designed to be conducted virtually via Microsoft Teams platform that is provided by the research institution, as well as in-person. The research team obtained the ethical approval from the institutional human research ethics before conducting the interviews. The authors followed the committee regulations, including the interview tools for recording as well as the obtaining the interviewee's signature in a consent form.

2.3. Data analysis

The analysis of data collected from the qualitative interviews included the following steps:

- ***Transcription:*** For virtual interviews, the automatic transcription service provided by Microsoft Teams was used. For the in-person interviews, Tascam DR-05 V2 digital audio recorder was used and then transcribed automatically using the Microsoft Office Online provided by the research institution. All transcripts have been revised through listening to the recordings and correcting the wrongly captured words. The transcripts were also edited by removing repeated words.
- ***Coding:*** Hybrid coding approach, both deductive and inductive, was considered in the data analysis as it has been adopted in previous studies [37]. Coding the transcriptions was carried out using ATLAS.ti software [38]. For the deductive approach, a set of priori defined codes focusing on the three main aspects were considered. These codes include T&P, F, and P&S-enabling factors. The inductive coding was also considered to obtain additional information from the data, such as perceptions about current technologies as well as perceptions about the applicability in future applications.

2.4. Patterns and themes

This part involves mapping the enabling factors in the context of façade design and construction processes, which includes design, production, assembly, operation and end of life phases. Considering these phases as the main focus in the analysis was due to the fact that it can illustrate where and when the key factors should be considered as well as achieved in order to enable the widespread application of SCIFs. Furthermore, it can indicates which phase most participants linked the factors to, as well as whether some factor were linked to one or more phase. Accordingly, mapping the factor is intended to establish a matrix to implement the solutions in product development.

3. Results

A total of 23 interviews were conducted between May 19th, 2022 till September 26th, 2022. All interviews, except one, were conducted virtually using Microsoft Teams, and all of them were conducted in English. The research team obtained the informed consent from all participants involved in the study. **Appendix B** summarizes the interviewees' profile that includes different information, such as their professional years of experience (Figure B1). Having an insight to the 23 interviewees, the most frequent educational and technical background among all interviewees was architecture (11 interviewees), followed by mechanical engineering (5 interviewees) and building physics (4 interviewees) (Figure B2). Fig. 3 provides information about the field of professional experiences. Taking into account the criteria considered to select participants (Section 2.3), Fig. 4 indicates how the many participants were involved in different types of projects. It is obvious that many participants interviewees were directly involved in the façade design and construction as well as the application of solar technologies, which stand for 22 and 18 interviewees, respectively. However, this is not the same for the application of solar cooling technologies in buildings, since it is still in the early adoption in real buildings. The following two points provide more information about their experience:

- ***Façade Design and Construction:*** All of the 23 interviewees declared to have been involved in the design phase (Figure B3).
- ***Application and/or Façade Integration of Solar/Solar Cooling Technologies:*** Many interviewees declared to have been involved in the application and/or façade integration of Photovoltaic panels compared to other solar/SCTs (Figures B4 and B.5).

All of interviewed participants are professionals working in Europe. Regarding the location of projects mainly experienced by these participants, most of them have worked in projects in the Netherlands, followed by Germany, Spain, and United Kingdom (Figure B6). However, 9 interviewees have been involved in projects outside Europe such as United States, United Arab Emirates and China (Figure B7).

The obtained findings from the 23 interviews are divided into two main parts. The first part presents the identified enabling factors from the deductive approach (Section 3.1). The second part presents the findings obtained from the inductive approach which are related to the perceptions about current technologies as well as perceptions about future applications (Section 3.2).

3.1. Key enabling factors

This section presents the key factors that have been identified to support the widespread application of SCIFs. It presents the results obtained from the deductive approach, which are related to the three main aspects. The frequency of identified factors in the context of the three main aspects, namely T&P,F, and P&S related aspects is summarized in Fig. 5 considering a descending order of the frequencies. **Appendix C** provides interpretations and descriptions of the identified key perceived factors (Table C1). The most frequently mentioned factors are product performance and efficiency, facilitating the delivery of product information to architects and clients, aesthetical acceptability, multidisciplinary teamwork, ability to customize products, ability to disassemble (Fig. 5). All of the identified factors have been linked to the P&S aspects, as well as majority of them have been linked to the façade design and construction processes as discussed in Table C1. For instance, product performance and efficiency as a T&P-attribute has perceived to be considered in design standards and guidelines for practitioners involved in the design phase. At the same time, the ability of product to maintain perform well during the operation phase has been perceived as a motivating factor that increases of clients and developers to adopt the technology. This is the same when considering the aesthetical acceptability of products, which has been linked to the design phase. Accordingly, visualising the link between the factors and process can provide a matrix to implement the solutions in product development. Hence, the factors were mapped in these processes based on the link that was declared by interviewees. Figures C1 and **C.2**

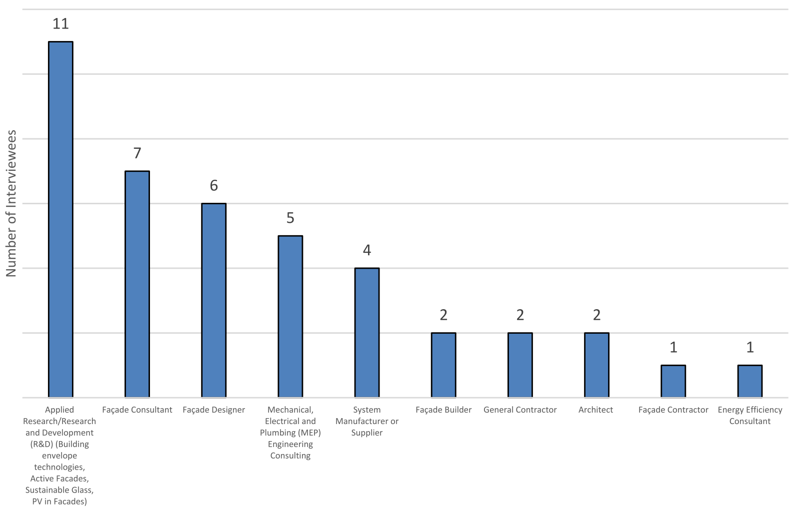

Fig. 3. Field of professional experiences.

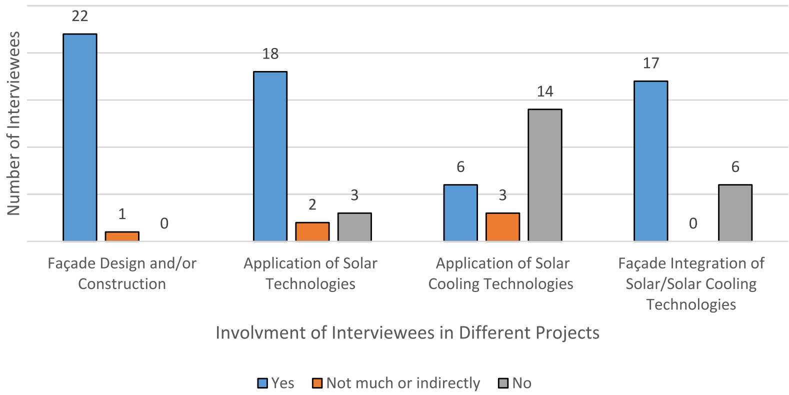

Fig. 4. Involvement of interviewees in different projects.

map the factors considering the a descending order of the frequencies indicated in both of Fig. 5 and Table C1. The factors were mapped in two separate figures (Figures C1 and **C.2**) in order to ensure the clarity and readability of the factors and their relations to different façade design and construction processes. Although majority of factors have been linked to the design phase, there couple of factors that have been considered to take place in both of design and production phases, including ability to customize products, ability to disassemble (this factor has been also linked to the end of life), Reusability, and Mass Production (Figures C1). The modularity as well as standardization and off-the-shelf products were linked to the there sequential phases, namely design, production, and assembly. Aspects related to the circularity aspects, including reusability as well as recyclability, has be considered to be taken into account during the design phase while such factors in order to be achieved at the end of life. However, there are few factors, such as the increase in the energy prices, taxes and fees, as well as the role of education and training of architects and engineers, that haven't been linked to any phase. Such factors are influenced by public bodies, such as energy policies as well as public educations institutions.

3.2. Prospects of future applications

These results were obtained from the inductive approach which are related to the perceptions about current technologies as well as perceptions about the applicability in future applications. The findings present perceptions related to integrating current solar cooling technologies into facades in terms of both factors supporting their application as well as concerns influencing their applicability. Additionally, the results outline the perceived suitable contexts for applying SCIFs, which include relevant building and project types. Finally, the findings show factors identified to affect the application of SCIFs based on the location and climate conditions.

3.2.1. Perceptions of the status of current technologies

Various factors have been perceived to support the widespread application of integrating current electrically-driven technologies based on photovoltaic (PV) panels and thermally-driven technologies based on solar thermal collectors (STC) (Fig. 6). On the other hand, different concerns were mentioned regarding the integration of both types of technologies into facades (Fig. 7). Table 1 provides a description and an interpretation to the perceived factors and concerns. According to Figs. 6 and 7 as well as Table 1, solar electrically-driven technologies (based on Photovoltaic modules) tend to be one of the most promising technologies. This obvious in terms of the number of the supporting factors and their frequencies. Apart of these two types of technologies, there are some perceptions related to the potential future improvements in the widespread integration of other technologies in the building industry, such as the Photovoltaic-thermal (PVT) technology. These perceptions were indicated by interviewees 1, 8, and 21. Regarding the widespread application of integrating thermoelectric (TE) technologies into façades, interviewee 19 declared different factors supporting its application which are related to the simplicity in the in the assembly and connections as well as in the working principle. On the other hand, the interviewee declared different concerns related to the façade integration of TE solar cooling technologies which are related to the low product performance and efficiency as well as some complexities in the working principles, such as problems with thermal bridges.

3.2.2. Perceptions of the future applications based on building type

Fig. 8 summarizes the perceptions of future applications based on building types. It is obvious that office buildings have been considered to be the most relevant building type for applying SCIFs due to the internal heat gains, such as office equipment, and the required cooling demand. The relevancy was also linked to the fact that office buildings are used during the daytime when solar radiation are available. The owners or the investors of office buildings have been perceived to be willing to invest in sustainable solutions. Public buildings, such as governmental or educational buildings, were considered to be relevant due to the possibility of having higher total project budget. Furthermore, they were considered to be suitable due to the potential of having an owner that can be representative of public bodies interested in lowering the energy consumption. On the other hand, public buildings have been perceived to be irrelevance by interviewee 15, considering an example of the Spanish context, due to the fact that in regulations associated with procurements in such type of buildings do not allow the selection of particular company supplying particular products.

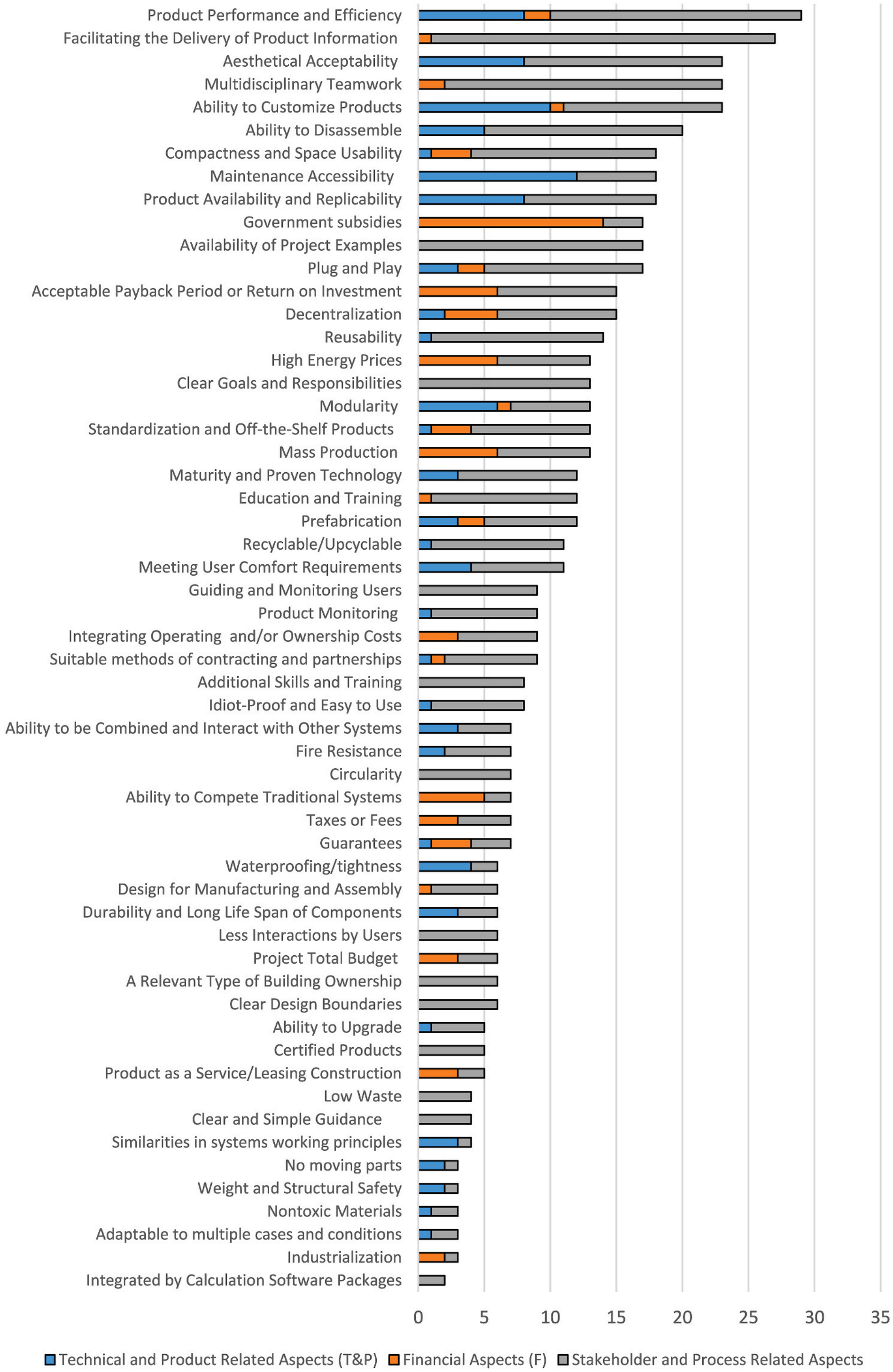

Fig. 5. Frequency of the identified key enabling factors.

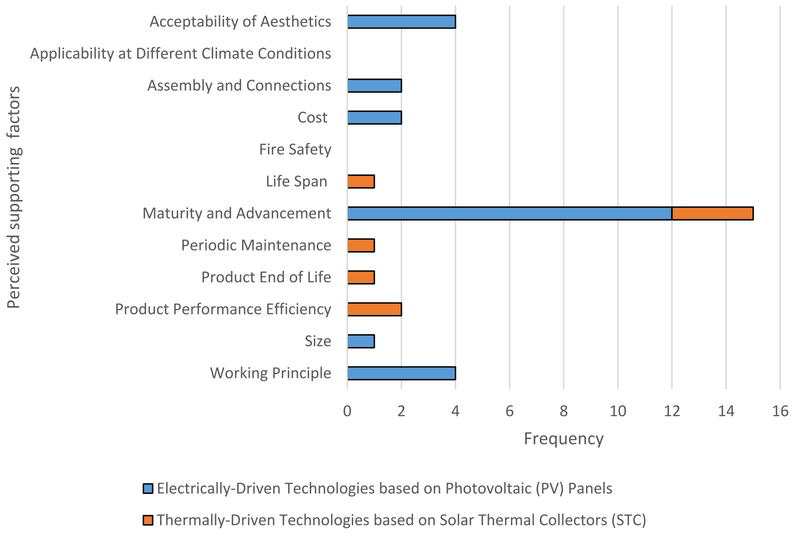

Fig. 6. Perceived factors supporting the widespread application of façade integration of current technologies.

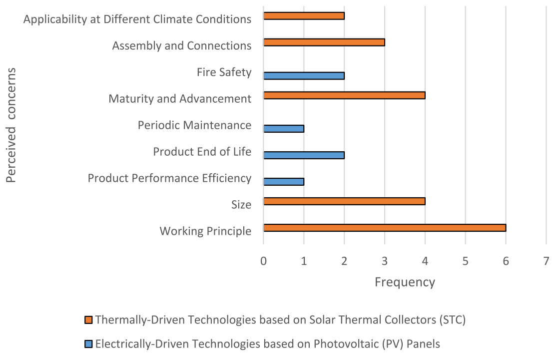

Fig. 7. Perceived concerns related to the façade integration of current technologies.

Regarding residential buildings, many interviewees have perceived to be irrelevant due various factors, such as low amount of cooling demand in such buildings in many European countries. Furthermore, the irrelevancy has been linked to the mismatch between the peak energy demand for cooling during the daytime where the building occupants are outside at workplaces. In addition, building occupants in residential buildings have been perceived to prefer living in traditional buildings, rather than implementing new technologies. Finally, residential apartment buildings having multiple tenants were perceived to be irrelevance due to the potential difficulties associated energy payments per apartment as well as convincing every tenant about new technologies.

3.2.3. *Perceptions of the Future Applications Based on Project Type*

As indicated in Fig. 9, new building construction projects have been perceived to be more relevant types projects, since integrating new technologies can be considered during early design stages where there is more design freedom. Renovation projects have been perceived to be relevant in the case of heaving compact products that can be integrated into building facades, especially when there are constraints with the available rooms or floor heights. Hence, building facades are have been considered a suitable option to integrate new technologies. On the other hand, renovation projects have been perceived to be irrelevant due to various factors, such as when local building regulations do not allow adding new technologies or doing any changes in existing buildings. Furthermore, the irrelevancy was linked to lack of having design freedom in such projects, such as in the case of having bulky components and the restrictions with the available space or the potential added high loads in existing building structures. Furthermore, issues related to disturbing building occupants have also been considered as a challenge when considering such technologies.

3.2.4. *Perceptions of the future applications based on the location and climate conditions*

As indicated in Fig. 10, there are various factors have been perceived to affect the application of SCIFs based on the location and

Table 1
Perceived factors and concerns related to the façade integration of current technologies.

Aspect	Electrically-Driven Technologies based on Photovoltaic (PV) Panels		Thermally-Driven Technologies based on Solar Thermal Collectors (STC)	
	Perceived as a supporting factor	Perceived as a concern	Perceived as a supporting factor	Perceived as a concern
Acceptability of Aesthetics	In comparison to other technologies, the aesthetics of current PV products has been perceived to be easily accepted by various stakeholders in the buildings industry, since they can have various colours that can be accepted regardless their performance.	–	–	–
Applicability at Different Climate Conditions	–	–	–	Some concerns are related are associated with the applicability of some thermally-driven technologies at different climate conditions.
Assembly and Connections	PV technologies have been perceived to be simple products, since the assembly and connections of components can be carried out easily on-sites.	–	–	The connections and installations of solar thermal technologies have been perceived to be complex due to the involvement of hydraulic components: Interviewee 14: "And then when you start with solar thermal and then even bringing solar cooling systems into the façade, then it becomes even more complex where the façade contractor says "I'm not doing hydraulic, I'm not doing water, I'm not doing electricity. I'm just installing simply set panels or façade units. But all these technical components that are more MEP driven is not my field of expertise""
Cost	The costs of PV technologies have been perceived to decrease within time and it is becoming more financially feasible, compared to other technologies, such as thermally-driven technologies.	–	–	–
Product End of Life	–	To minimize the carbon footprint, building regulations support the low amount of wastes generated at the end of life of building products. However, the amount of waste related to the end of life of PV technologies has been perceived to be crucial.	Thermally driven technologies are perceived to be have less harmful effect to the environment at their end of life.	–
Fire Safety	–	The fire safety associated with some current PV technologies has been perceived a critical concern affecting the widespread application.	–	–
Life Span	–	–	Some of the thermally driven technologies are perceived to have long life span.	–

(*continued on next page*)

Table 1 (*continued*)

Aspect	Electrically-Driven Technologies based on Photovoltaic (PV) Panels		Thermally-Driven Technologies based on Solar Thermal Collectors (STC)	
	Perceived as a supporting factor	Perceived as a concern	Perceived as a supporting factor	Perceived as a concern
Maturity and Advancement	The maturity of PV technologies has been perceived to be in an advanced stage with ongoing improvement. The level of knowledge in the building industry regarding their integration into building facades is perceived to have increased during the last years due to the availability of specialized companies working on them, additionally PV technologies have been perceived to have flexibilities in their use considering different sizes of buildings.	–	There are some perceptions that are related to the future improvements in the use of solar thermal technologies in buildings, such as the use of flat plate collectors that can be customized in terms of colours.	The development and widespread application of façade products integrating solar thermal technologies is perceived to be slower than solar electrically-driven technologies.
Periodic Maintenance	–	The concern has been perceived by Interviewee 2, which is related to number of periodic maintenance required for the system and the time consumed in maintaining the technologies: "The maintenance required for the photovoltaic and the compression system usually is more time consuming and should be done more regularly, especially for the compression cooling system. It has to be maintained at least once a year with the re-fuelling of the cooling agent, the Freon and these gases"	The amount of periodic maintenance can be low for some absorption chillers: "You have the absorption cooling for example where you only have to maintain it once every two years" (Interviewee 2).	–
Product Performance Efficiency	–	Some solar thermal technologies have been perceived to have higher efficiencies compared to some of the solar electrically-driven technologies.	Some of the solar thermally-driven cooling technologies can reach high efficiencies: Interviewee 2: (1) "while solar thermal can reach 80% or higher depending on the type of collector and quality and so on", Interviewee 22: (2) "Although if you have good use cases, you can collect more energy overall with the thermally-driven technologies and if you can make use of them they might be worth well considering".	–
Size	PV technologies has be considered to be simple technology due to their compact sizes compared to thermally-driven technologies.	–	–	The application of some of the solar thermal cooling technologies can be challenging in small size projects. They have been considered to have complexities in terms of their sizes, due to the availability of bulky components.
Working Principle	PV technologies have been perceived to have simpler working principles compared to other technologies, since they neither involve the use of any flowing liquids nor the use of hydraulic components.	–	–	The working principles of some thermally-driven technologies have been perceived to be complex as decentralizing solar thermal cooling technologies requires incorporation of different types of fluids that needs to be circulated within the system. Furthermore, other concerns have been perceived are related to the potential risks of water freezing, water tightness, as well as dealing with the collected heat that cannot be used for other purposes, compared to the electricity generated by photovoltaic.

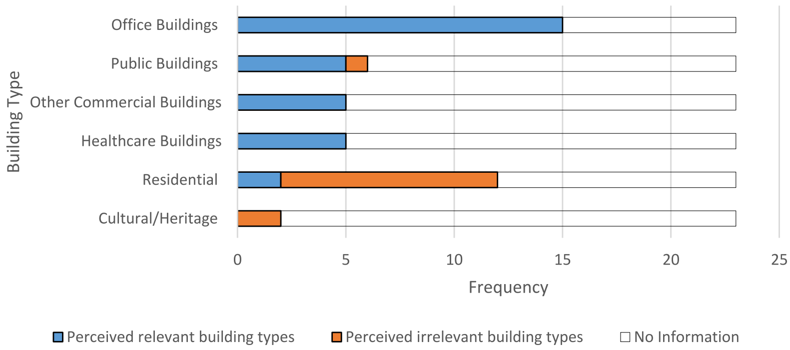

Fig. 8. Perceptions of the future applications based on building type.

climate conditions, which are as follows:

- ***Geographic Location:*** Geographic locations of buildings has been considered a key factor affecting the application of SCIFs. Southern European countries, such as Italy, Greece, and Cyprus, as well as Mediterranean climates were perceived to be relevant applying such technologies. Middle Eastern countries, such as Saudi Arabia and United Arab Emeritus, were also identified to be suitable for such technologies.
- ***Urban Effect:*** The urban effect of surrounding buildings been identified as a key factor affecting the application of SCIFs. Avoiding the shading effect has been perceived to be taken into account in order to ensure proper performance of such technologies.
- ***Building Orientation:*** The building orientation and the façade exposure to solar radiation has been considered to affect the application of SCIFs, such as considering the application in south oriented facades in Northern areas.
- ***Solar Radiation Availability:*** The availability of solar radiation has been identified to be a key factor influencing the applicability of SCIFs. Different perceptions have been mentioned by the interviewee. Some interviewees have mentioned the importance of having more solar radiation areas, whereas others have mentioned the importance of having moderate amount of solar radiation to avoid overheating issues. On the other hand, interviewees 14 and 23 declared that such factor depends on every project.
- ***Cooling Demand in Buildings:*** Cooling demand in buildings has been perceived to affect the applicability of SCIFs. Buildings located in areas where cooling demands are high have been considered to be more relevant, such as cooling demands are required more than six months a year or they count for more than 70% of the total energy consumption.
- ***Humidity Effect:*** Having humid climates has been identified as a key factor affecting the application of SCIFs, since the applicability of some thermally-driven technologies can be challenging due to difficulties associated with heat rejection.

4. Discussion

The aim of this study was to identify key perceived enabling factors and prospects of future applications related to the widespread application of SCIFs from the point of views of various professionals, including participants worked in projects involving the application or façade integration of solar/SCTs. Having an insight into the identified and mapped key factors in Fig. 5, Table C1, Figures C1 and **C.2**, it is obvious that majority of factors have been linked to the design phase. Although this can be related to the fact that all of the 23 interviewees declared to have been involved in the design phase of building facades (Figure B3), early decisions regarding the application of new technologies should be taken into account early stages in order to simplify the installation of components.

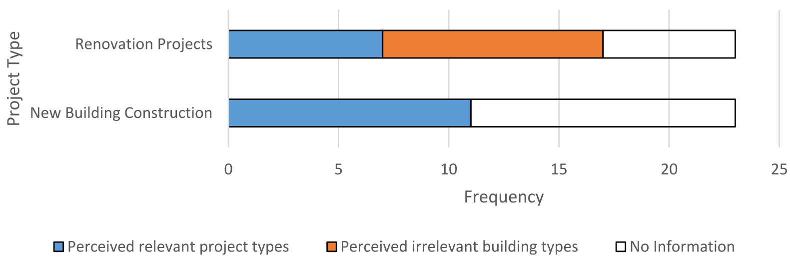

Fig. 9. Perceptions of the future applications based on project type.

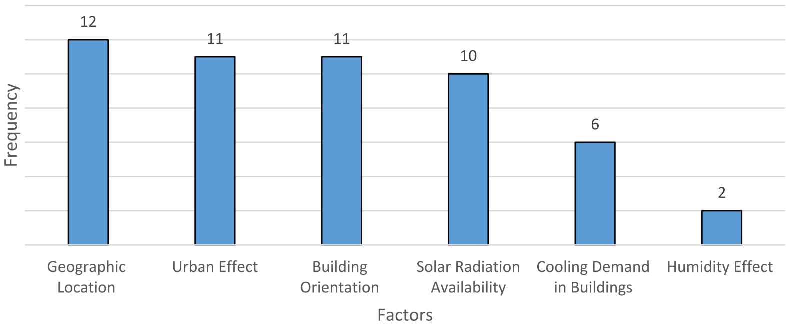

Fig. 10. Perceived factors affecting the application of SCIFs based on the location and climate conditions.

Furthermore, such decisions consider the importance of having a proper system operation during the use phase in order to avoid various issues related to the inefficient use of the technology. Accordingly, it is essential to tackle such critical phase, which may include the involvement of different identified enabling factors as key performance indicators to be used in the design and evaluation of SCIFs. Furthermore, tackling the design phase may take into account the importance identifying key stakeholders involved in the project, since the multidisciplinary teamwork and facilitating the delivery of product information to architects and clients were among the most frequently mentioned factors. However, the determination of such factors requires considering different aspects, including type of technology to be integrated into the façade, the nature of the project, as well as the local context of the building industry. Accordingly, the applicability of the perceived enabling factor obtained from this exploratory study depends on various aspects including the project size and stakeholders involved, location, technologies to be considered, building typology, project type (existing various newly built). For example, although prefabrication has been identified as an enabling factor, Interviewee 1 has some concerns related to the fact that on-site works are still common in many countries (Table C1).

Apart from the design phase, majority of the key factors that have been linked to the end of life phase are the ones that are related to the circularity concepts as well as R-strategies, such as the reusability and recyclability. This can be due to the fact that several efforts and initiatives are moving towards minimizing the amount of waste generated from the building industry.

Although standardizing and customizing products tend to be two opposite factors, both of them have been considered to enable the widespread application. Standardization have been identified reduce the production costs, as well as increase the knowledge and experience of architects, since they can become more familiar with the same product when it is used for more than one project. On the other hand, the ability to customize, including colours, shapes, and/or sizes was perceived to support the widespread application, especially when considering the role of aesthetics in the widespread application. However, the mass customization, such as in the automobile industry where the core of products can be similar with different external layers, have been declared by interviewee 4 to enable the widespread application of SCIFs.

Having an insight into the perceptions of the status of current technologies, it is obvious that maturity and advancement of PV technologies have been perceived the main factor supporting the widespread application of integrating current electrically-driven solar cooling technologies into building façades. Although this perception can be linked to the fact that majority of interviewees have worked in projects involving the application (17 interviewees according to Figure B5) or façade integration (13 interviewees according to Figure B4) of solar technologies using PV panel, this cannot deny the fact that PV technologies have been improved within the time.

Although various justifications have been mentioned regarding the relevancy of office buildings as suitable building types to apply such technologies, such relevancy might be different in contexts other than Europe. Regarding the relevancy or irrelevancy of applying SCIFs in renovation projects, it should be noted that various aspects can affect the application of such technologies in existing buildings, such as the compactness of the technology as well as the project nature, including the size of the building.

5. Conclusion

Solar cooling technologies (SCTs) have the potential to reduce primary energy consumption for space cooling. Building façades provide an opportunity to integrate SCTs because they provide external surfaces exposed to solar radiation, and also have an impact on the indoor thermal comfort. Enabling the widespread application of integrating SCTs into façades can be challenging due to the involvement of technical and product (T&P), financial (F), as well as process and stakeholder (P&S) related aspects. Identifying key enabling factors in the context of various aspects is an important step providing relevant knowledge for implementing solutions supporting the widespread application. Accordingly, this study aims to identify main factors enabling the widespread integration of SCTs in façades from the point of view of various experts. An interview guide was designed to tackle main aspects to be considered for supporting the widespread application, including T&P, F, and P&S related aspects. Different criteria were considered to select the interviewees during the data collection, such as having participants worked in projects involving the application or façade integration of solar/SCTs in buildings. The data analysis involved a hybrid approach, combining deductive and inductive coding. The findings revealed that there are key factors supporting the widespread application, such as product performance and efficiency, multidisciplinary teamwork and facilitating the delivery of product information to architects and clients, aesthetical acceptability and the ability to customize products. The enabling factors were mapped in the context of façade design and construction processes to establish a matrix for implementing solutions in product development. The results also indicated that solar electrically-driven technologies (based on Photovoltaic modules) tend to be one of the most promising technologies. Furthermore, office buildings have been perceived to be one of the most relevant types of buildings to be considered for such technologies. The identified enabling factors and prospects of future applications of solar cooling integrated facades (SCIFs) contribute to expand the boundaries of knowledge in the field of building product development. The established matrix of enabling factors obtained from this exploratory study provide information that can be considered and investigated in future works related to the to the development of frameworks supporting the widespread application of SCIFs, since the applicability of perceived factor depends on various aspects. The aspects include project size and stakeholders involved, location, technologies to be considered, building typology, project type (existing various newly built). Accordingly, future framework developments can consider the applicability of particular SCTs in particular contexts, such as investigating the future application of these technologies in newly built office buildings.

This study was limited to the key perceived enabling factors and prospects of future applications based on the European perspective. Accordingly, the findings of this study can be more relevant for the European context. Accordingly, future research scope can investigate the application of SCIFs in a relevant European context, such as newly built office buildings, through considering some of identified enabling factors as Key Performance Indicators (KPIs) to evaluate the developed concepts of façade products.

Author statement

Hamza Hamida: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing - Original Draft, Writing - Review & Editing, Formal analysis. Thaleia Konstantinou: Conceptualization, Methodology, Supervision, Review & Editing. Alejandro Prieto: Conceptualization, Methodology, Review & Editing. Tillmann Klein: Conceptualization, Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data supporting this research findings is openly available at this link https://doi.org/10.4121/bead775f-2674-477a-85b5-cf8446291348.v1.

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This study was approved by the Human Research Ethics Committee (HREC) at TU Delft on 04-April-2022. The research team obtained the informed consent from all participants involved in the study. The authors followed the committee regulations, including the interview tools for recording as well as the obtaining the interviewee's signature in a consent form. The audio-recording for the virtual and in-person interviews was conducted by Microsoft Teams platform and Tascam DR-05 digital recorder, respectively. The interviewees signed the consent form virtually that agreed on the allowing audio-recording of the interviews that will be stored on the institutional storage drive where it will has a restricted access only among the study team. Furthermore, they agreed on using, processing, and publishing the anonymized transcriptions of the interviews. Accordingly, the data supporting this research findings is openly available at this link https://doi.org/10.4121/bead775f-2674-477a-85b5-cf8446291348.v1.

Appendix A. Interview questions

A.1. Opening question

- In your experience, what is the current level of knowledge in the building industry regarding the application of multifunctional façade components integrating solar cooling technologies?
- In your experience, what are motivating factors for the application of multifunctional façade components integrating solar cooling technologies?
- In your experience, what are the concerns regarding the application of multifunctional façade components integrating solar cooling technologies?
- How would you address such concerns?

- How can the type of project, such as new building construction or building renovation, influence the applicability of solar cooling integrated façades?
- How can the building type (e.g. office, residential, heath care, educational, etc) influence the applicability of such façade products?
- In your experience, how do the locations and climate conditions of buildings affect the performance of solar cooling integrated façades?
- Which locations and climate conditions would you suggest for applying façade products integrating solar cooling technologies?
- Do you think the choice of solar cooling technology, namely electrically-driven or thermally-driven, would affect the application of such façade products in a particular building project?

A.2. Key questions

A.2.1. Questions about technical and product-related aspects

- In your opinion, what makes solar cooling integrated façades complex products?
- How would you address these complexities?
- How could we address challenges related to the space availability or interrupting other building services?
- What are the key aspects to consider for the maintenance and durability of solar cooling integrated facades?
- How do you see the role of aesthetics in the widespread application of building façades integrating solar technologies?

A.2.2. Questions about financial aspects

- In your experience, how can the industry develop affordable and financially feasible façade products integrating such technologies?
- What are the potential financial incentives that can support the widespread application of solar cooling integrated façades?

A.2.3. Questions about process and stakeholder related aspects

Kindly have a look at the following graph (Fig. A.1).

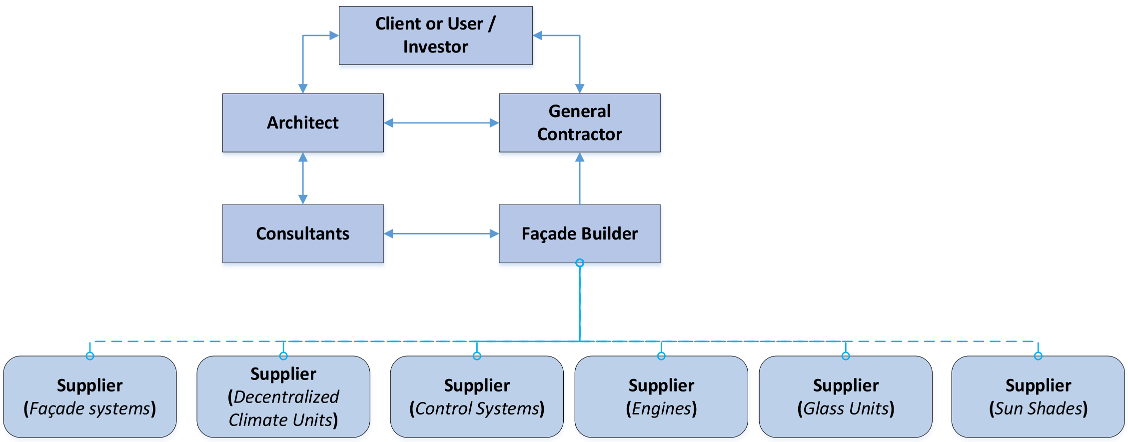

Fig. A.1. Relationships between stakeholders in façade construction [26].

- In your experience, which of these stakeholders can support the application of solar cooling integrated façades?
- How can we increase the knowledge and experience of architects/engineers regarding the technical aspects of integrating such technologies into building facades?
- What are the key elements that should be in standards and guidelines for architects and engineers related to the integration of solar cooling technologies into façades?
- How can the industry increase the variety of products to attract customers to apply solar cooling integrated façades?
- How can we increase the interest of designers, developers, and clients in solar cooling integrated façades?
- How can changes in building regulations affect the widespread application of solar cooling integrated façades?
- What about changes in energy policies?

Kindly have a look at the following graph (Fig. A.2).

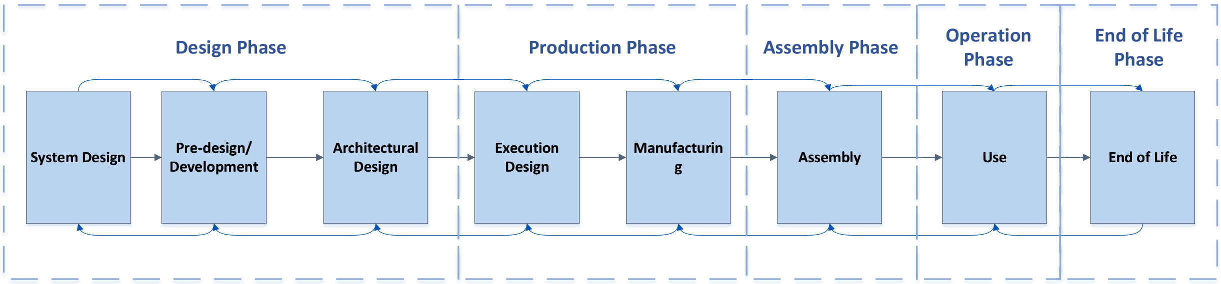

Fig. A.2. Processes of façade products [26].

- In your experience, which phase is key for boosting the integration of solar cooling technologies into building façades?
- What are the main aspects to consider during the design phase of solar cooling integrated façades?
- In your opinion, how can we achieve a closer collaboration between various stakeholders and disciplines during early design stages of the of solar cooling integrated facades?
- What are the key aspects to consider during the production phase of solar cooling integrated façades?
- What about the assembly phase of solar cooling integrated façades (including the required workforce)?
- What about the operation phase of solar cooling integrated façades (including the end users' knowledge)?
- What about the end of life of solar cooling integrated façades?

A.3. Closing Questions

- Do you have any final remarks about the widespread application of solar cooling integrated façades as building products?
- What do you think about the application of solar cooling integrated façades for enabling energy transition?
- Do you mind proposing potential participants to be interviewed for this study?

Appendix B. Interviewees' profiles

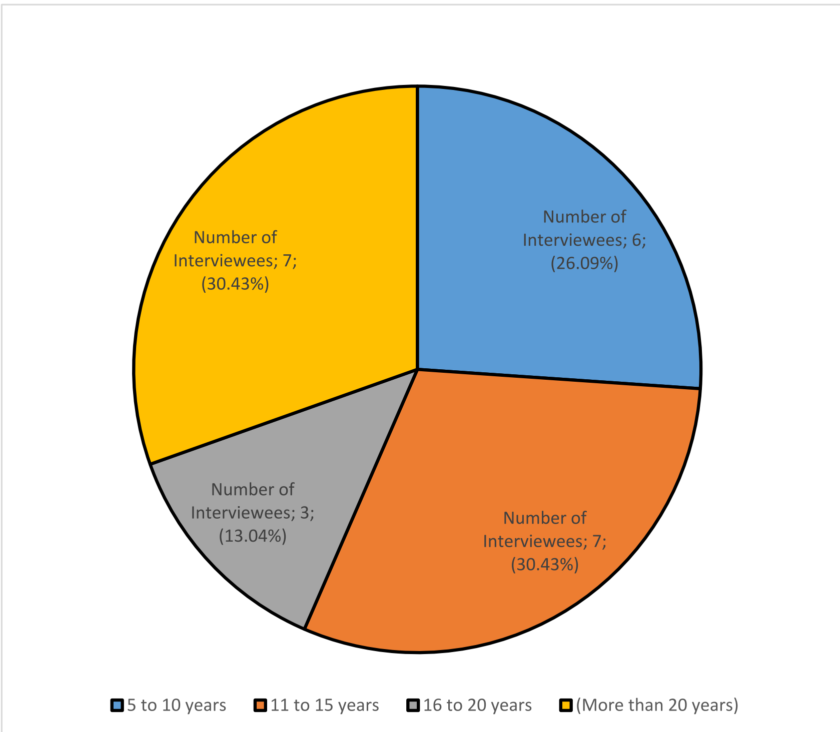

Fig. B.1. Professional Years of Experience.

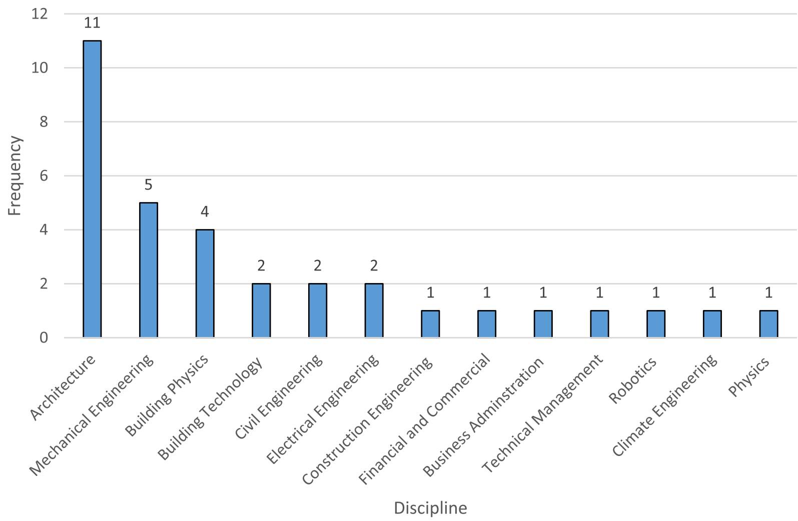

Fig. B.2. Educational and Technical Background.

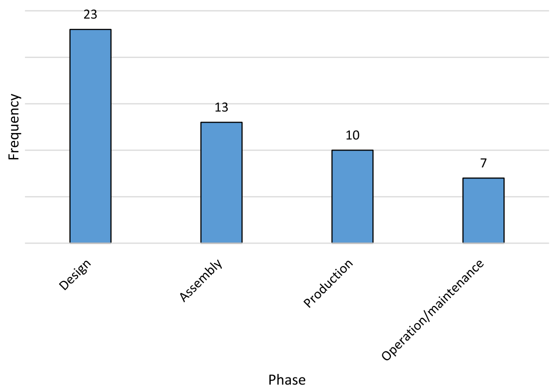

Fig. B.3. Phases have been Mainly Involved in the Façade Design and Construction.

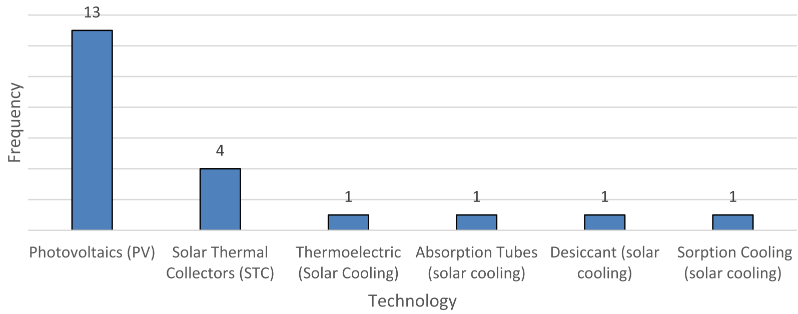

Fig. B.4. Experience of Interviewees on the Integration of solar/solar cooling technologies into Facades.

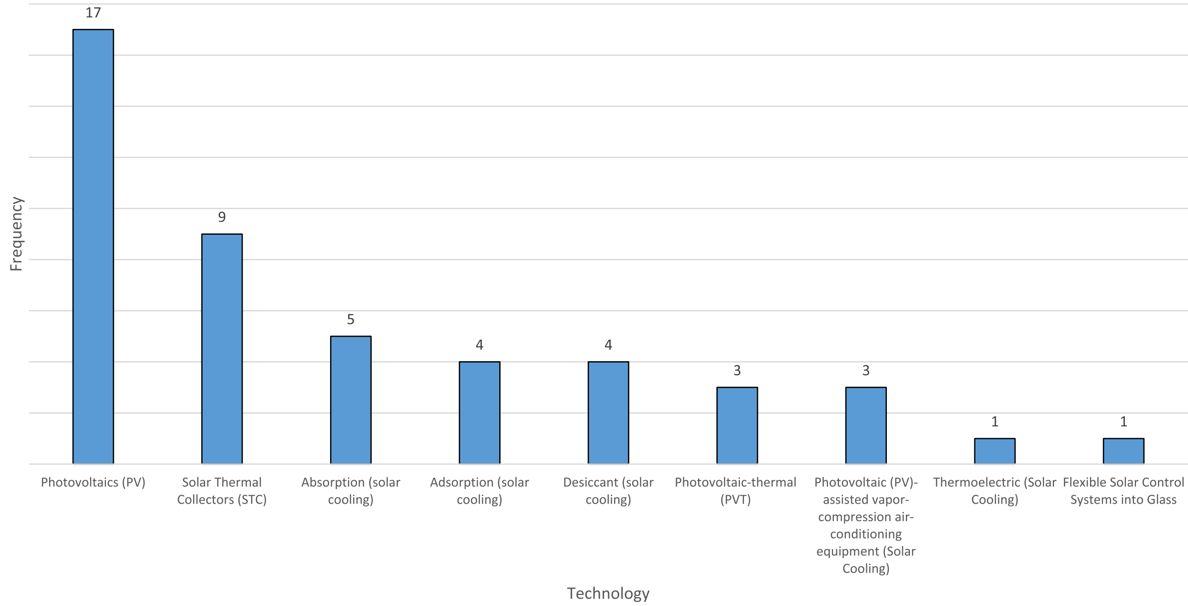

Fig. B.5. Experience of Interviewees on the application of solar/solar cooling technologies in buildings.

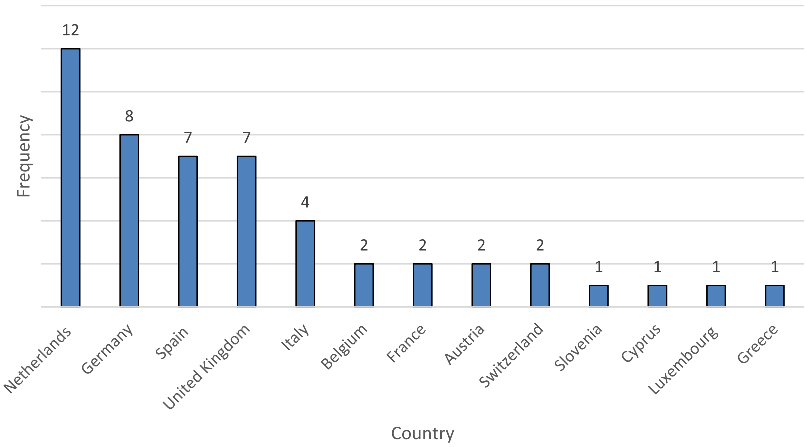

Fig. B.6. Locations of projects mostly experienced by interviewees (in Europe).

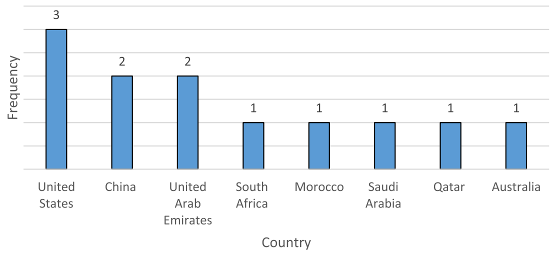

Fig. B.7. Locations of projects experienced by interviewees (outside Europe).

Appendix C. Identified key enabling factors

Table C.1
Identified key enabling factors

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Product Performance and Efficiency	8	2	19	29	The ability of the whole façade system, that includes various components such as collectors and cooling devices, to maintain proper performance and efficiency during the operation phase has been perceived to support the widespread application. The whole facade system should be able to still perform as a normal façade even when there are potential malfunctioning in a certain component. The factor was considered to be a financial incentive supporting the widespread application, as well as a motivating and interest factor that increase in the interest of designers, developers, and clients. It has been perceived to be considered in standards and guidelines for practitioners involved in the design phase
Facilitating the Delivery of Product Information	**0**	**1**	**26**	**27**	Facilitating the delivery of product information, such as product marketing, has been considered to enable developing financially feasible facade products, and also increasing the knowledge and experience of architects and engineers, as well as the interest of designers and clients. The factor has been linked to early design stages where architects should have clear information about products, such as the investment costs, sizes and dimensions, as well as the appearance, including simple sketches instead of providing technical specifications. Delivering such information can be carried out in different ways, such as arranging frequent meetings between architects and suppliers, consultants, or facade builder. Other approaches include marketing and advertisements in webinars, fairs, and sponsored events
Ability to Customize Products	**10**	**1**	**12**	**23**	The ability to customize, including colours, shapes, and/or sizes has been perceived to support the widespread application. Most of the interviewees have related this enabling to the role of aesthetics in the widespread application. Although it may depend on the type of technology and the materials used, the factor was considered to be a financial incentive, especially when materials and components can be easily customized by suppliers and/or manufacturers. The factor has been perceived to increase of the interest of architects and clients, especially when architects have some freedom during the design where they have different options to choose from in order to generate their own unique design. The factor was linked to the production phase where there should be some fixed and adaptable elements, such as the case of mass customization in the automobile industry where the core of products can be similar with different external layers
Multidisciplinary Teamwork	**0**	**2**	**21**	**23**	Multidisciplinary teamwork consisting of experts from different fields, such as architectural as well as mechanical, electrical and plumbing (MEP) disciplines, was considered to contribute to the development of affordable and financially feasible products. The experts can focus of a particular technology and investigate its application, while considering different boundaries, such as a project total budget. Considering this factor during design phase can be carried out through different approaches. For example, it has been perceived that experts from specialized companies can be involved in the design phase in order to support architects. The factor was also linked to the assembly phase where technology suppliers can provide clear instructions related to the assembly of components to the installing company, but at the same time they can be present on-site in order proper installation
Aesthetical Acceptability	**8**	**0**	**15**	**23**	Aesthetical acceptability has been perceived to have a key role of aesthetics in the widespread. Different perceptions have been considered to illustrate the aesthetical acceptability, such as having a normal facade appearance while others linked it to its ability to acceptable for many years. Such enabling factor has been perceived to increase the interest of interest of designers, developers and the clients. It has been linked to the effect of changes in building regulations in the widespread application. Such factor was identified to be taken into account during the design phase. Some of the concerns related to the aesthetics include having certain parts from the façade that have different appearance from the whole building. Others are related to the risk of having a perception that such façade is outdated after some years. Some concerns are related to the fact that having policies that are focusing on the production of renewable sources of energy without taking into account the aesthetics of the built environment.
Ability to Disassemble	**5**	**0**	**15**	**20**	The ability to disassemble components was considered to be a key factors related to the maintenance and durability, where components are required to be repaired off-site or replaced. This factor has been linked to the design and production phases in order to ensure that components can be easily removed easily at their end of life, where the system can be upgraded or some of the disassembled components can be reused or recycled
Product Availability and Replicability	**8**	**0**	**10**	**18**	Product availability and replicability was perceived to be an important factor related to the maintenance and durability, especially in the case of having sudden damages or malfunctions. The factor was considered to be taken into account during the design phase for both of the operation and end of life phases. This is due to the fact that the life span of some of the integrated technologies can be shorter than the life of the main facade
Maintenance Accessibility	**12**	**0**	**6**	**18**	The ability to access was perceived to be dependent on the size and height of the building. Having an inside accessibility is perceived to be relevant for high-rise buildings in order to avoid costs associated with the use of external equipment. On the other hand, external product accessibility has been perceived to have an advantage that is related to avoiding the disturbance of building occupant. Such factor has been perceived to be taken into account during the design phase in order to ensure proper product accessibility during the assembly and operation phases.

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Table C.1 (*continued*)

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Compactness and Space Usability	**1**	**3**	**14**	**18**	Miniaturizing façade products integrating solar cooling technologies has been considered to be one of the potential financial incentives, since it can provide more useable space for building owners where they can be rentable. Accordingly, this can attract various customers, such as owners of high-rise buildings where there are space limitations on the roof, to apply such products. Such factor has been considered to be taken into account during early design stages.
Plug and Play	**3**	**2**	**12**	**17**	This factor has been perceived to enable plugging and unplugging components easily. Plug and play systems was considered to support the development of affordable and financially feasible façade, since the on-site combination of different fields, such as mechanical and building installations, can be costly. Such factor was linked to the production phase, in order to avoid any concerns associated with the assembly phase. It has been perceived to be able to address contractors concerns who are not experts in dealing some with technologies, such as having uneducated labours that are required to handle installing components.
Availability of Project Examples	**0**	**0**	**17**	**17**	The availability of relevant project examples indicating the technological application was found to support the widespread application. Such factor was considered as a main contributor to increase the knowledge and experience of architects and engineers, as well as to increase the interests of other stakeholders, such as clients and developers. There were different perceptions about demonstrating a relevant project example, such as built prototypes, small pilot projects, or real projects.
Government subsidies	**0**	**14**	**3**	**17**	Government subsidies, either in a local, national, or European level, has been perceived to be a key factor supporting the development of affordable and financially feasible facade products, since it can address concerns related to high investment costs and long payback periods. Such enabling factor has been linked to the both of design and assembly phases. It has been also perceived to be linked to the effect of changes in energy policies in the widespread application of façade products integrating solar cooling technologies. Although it was considered to be a key enabling factor, some concerns associated with such factor was mentioned by interviewees 3 and 5. The concerns were related to the availability and political acceptability related to providing such the incentives.
Decentralization	**2**	**4**	**9**	**15**	Having decentralized SCIFs was perceived to address challenges related to the space availability or interrupting other building services, as well as reducing the amount of failure rates due to the redundancy in ventilation units. It was also considered to have a key role in minimizing costs related to installing centralized ventilation systems, such as costs related air ducts. Furthermore, having decentralized ventilation systems that are based on renewable sources of energy reduce the electricity bills, especially when energy prices are increasing. They tend to be a motivating factor to be included in building regulations. Moreover, the factor was identified to be considered between the design and end of life phases, since it can be compared with other options, such as centralized systems, as well as to be considered for renovation works take place in existing buildings. Although it has been identified as an enabling factor, there are some concerns related to it. One of them is related to the potential increase in the use of materials and components, which can have some issues from the circularity point of view. Furthermore, such increase in the use of components may lead to an increase in maintenance requirements. Furthermore, decentralized solutions might be more expensive than centralized ventilation systems.
Acceptable Payback Period or Return on Investment	**0**	**6**	**9**	**15**	The ability of the façade products to have an acceptable payback period or return on investment was perceived to demonstrate the financial feasibility. It has been indicated that most people would prefer short periods, such as 10–15 years, as a main goal. However, it has been declared that when clients start to accept longer periods, such as 20–25 years, the widespread application of such products would be higher. The ability to demonstrate such factor using relevant graphs can increase the interest of various stakeholder.
Reusability	**1**	**0**	**13**	**14**	The ability of such façade products to be reusable after disassembling it has been perceived to be a key factor supporting the widespread application. Such factor has been recognised in design, production, as well as end of life phases. However, majority of interviewees mentioned it when discussing key aspects to consider for the end of life.
Mass Production	**0**	**6**	**7**	**13**	Mass production was considered to be one of main factors contributing to the development of affordable and financially feasible products. The increase in the production volume of standardized products can reduce the prices of products. However, the mass production depends on the demand and may requires some time to be achieved, since the demand of new innovative products is lower at the beginning. This factor was linked to the design and production phases in order to reduce the cost of façade products.
Standardization and Off-the-Shelf Products	**1**	**3**	**9**	**13**	The availability of standardized and off-the-shelf façade products was perceived to be a key factor to be considered for the maintenance and durability. Having such products was considered to reduce costs, since standardized products can be easily produced and while reducing the production costs. The availability of standardized façade can contribute to increase the knowledge and experience of architects, since they can become more familiar with the same product when it is used for more than one project. Accordingly, this can accelerate the design phase, as well as it can also help in having standardized

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Table C.1 (*continued*)

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Modularity	**6**	**1**	**6**	**13**	manufacturing which results in lower cost of products. Moreover, the assembly phase of building facades has been expected to be easier when dealing with standardized products. Having a modular SCIFs system, such as in many office buildings, was considered to be an important factor for the maintenance and durability, since it can facilitates accessing, disassembling, and replacing components. Interviewee 14 linked the modularity with standardization as key enabling factors supporting the development of affordable and financially feasible facade products that can be easily produced. Modularity has been perceived to be considered in design guidelines for architects. Considering such a key factor during the design phase can facilitate the achievement of mass production. It has been also linked to the assembly phase when considering plug and play systems and the connectivity of components. Furthermore, the modularity has been perceived to be a key factor to be consider for the end of life when considering the disassembly of the integrated technology that would have shorter life span than the main facade.
Clear Goals and Responsibilities	**0**	**0**	**13**	**13**	The ability to define and clarify goals and responsibilities of all parties, including interfaces, points of separation, and handover, has been perceived to enable achieving a close collaboration among various stakeholders during early design stages. It involves that all parties are interested in the technology and understand each other's concerns, roles, and goals. Such factor can be achieved by having a transparency among all stakeholder, which can be discussed in webinars and workshops including key actors. Having well-defined interfaces can be considered for the assembly phase, such as defining companies supplying the mounting systems for installers.
High Energy Prices	**0**	**6**	**7**	**13**	The increase in the energy prices was considered as a potential financial incentive supporting the widespread application of SCIFs facades. Such factor has been perceived to increase the interest of various stakeholder, such as designers, developers and clients, in the application of such façade products. It has been linked to the effect of changes in energy policies as well as building regulations in the widespread application.
Prefabrication	**3**	**2**	**7**	**12**	Having prefabricated SCIFs facades has been perceived to address challenges related to the space availability or interrupting other building services, as well as contribute to improve the quality of components, since they are assembled in a controlled environment. Prefabrication was identified to be a key enabling factors to be considered for the assembly phase, since it can ensure the quality of façade products and also minimize the amount of work to be carried out on-site. Therefore the installation time can be reduced. Although prefabrication has been identified as an enabling factor, Interviewee 1 has some concerns related to the fact that on-site works are still common in many countries.
Education and Training	**0**	**1**	**11**	**12**	Educating and training architects and engineers during their studies about such technologies can support the widespread application. This includes providing courses in schools of architecture and engineering that cover aspects related to design calculations as well as the properties of cooling systems. Furthermore, this includes educating and training current practitioners in the industry through providing online courses or certified training programs by specialized associations, such as associations related to the metal windows and facades. Such factor has been perceived to enable the development of affordable and financially feasible facade products.
Maturity and Proven Technology	**3**	**0**	**9**	**12**	Having mature and proven technologies that can work as it is supposed to do without any defect can enable the widespread application. Such factor has been perceived to increase the interest in SCIFs. The ability to have proven concepts that can be integrated into the façade was identified to be taken into account during the design phase.
Meeting User Comfort Requirements	**4**	**0**	**7**	**11**	The ability of such façade products to meet the user comfort requirements was perceived to be a key factor to be considered in standards and guidelines for practitioners involved in the design phase to ensure the comfort of users living behind the façade during the operation phase, such as avoiding any potential noises generated by the integrated elements.
Recyclable/Upcyclable	**1**	**0**	**10**	**11**	The ability of façade products to be recyclable/upcyclable, such as considering the use of aluminium, has been perceived to support the widespread application. Such factor has been recognised in both of design as well as end of life phases. However, majority of interviewees mentioned it when discussing key aspects to consider for the end of life.
Suitable methods of contracting and partnerships	**1**	**1**	**7**	**9**	Suitable methods of contracting have been perceived to be a key factor related to the maintenance and durability of facades products, such as having maintenance contracts provided by installers or another specialized company. Such factor can address concerns related to any malfunction. Although it depends on the technology and the project nature as well as other aspects, having an appropriate contracting method or partnerships among the relevant stakeholder was perceived to support the development of affordable and financially feasible products. Such key factor was perceived to enable a close collaboration during design phase as well as to ensure an appropriate operation phase. Different methods of contracting were mentioned by interviewees, such as Integrated Project Delivery (IPD) contracts and Design-Build-Maintain-Operate (DMBO) contracts.
Integrating Operating and/or Ownership Costs	**0**	**3**	**6**	**9**	Operating and/or ownership costs were considered as key aspects to be taken into account for the maintenance and durability of such façade products. Having clients who taking into account these aspects was perceived to enable the widespread application. The ability to develop a total cost of ownership to clients has been identified as a main financial incentive. Such factor has been perceived to be considered during early design stages.

(*continued on next page*)

Table C.1 (*continued*)

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
					Taking into account such type of costs was considered as a motivating factor for various stakeholders, due to the increase in the energy prices.
Product Monitoring	**1**	**0**	**8**	**9**	The ability to monitor façade products integrating such technologies has been perceived to be a key enabling factor, since it can ensure the optimal use of the product. Such factor has been linked to the operation phase where actual product performance can be compared with the designed one. Furthermore, it was considered to be taken into account in building regulations to ensure that the installed technologies are used properly.
Guiding and Monitoring Users	**0**	**0**	**9**	**9**	The ability to guide and monitor users has been perceived as a key factor to be considered for the end user knowledge during the operation phase, in order to avoid the misuse of the technology.
Idiot-Proof and Easy to Use	**1**	**0**	**7**	**8**	Idiot-proof products that can be easily used, such as having a simple interface on a mobile phone, was perceived as a key enabling factor to be considered for the end user knowledge during the operation phase. Furthermore, it has been identified to increase interests of clients, designers and developers.
Additional Skills and Training	**0**	**0**	**8**	**8**	Having additional skilled and trained labours during the production and assembly phases was identified to supporting the widespread application. This can be in the form of having skills related to the installation of heating, ventilation, and air conditioning (HVAC) components, in addition to the facade components.
Guarantees	**1**	**3**	**3**	**7**	Providing suitable guarantees that cover the whole system for a relevant period of time, e.g. 10–25 years, has been perceived as aanan main factor to be considered for the maintenance and durability. The ability to guarantee the system performance for a certain amount of time has been identified as a financial incentive supporting the widespread application. This factor has been linked to the design phase where designers can be aware about the its availability. It has been also linked to the assembly and operation phases, where the whole system can be guaranteed by one party for a certain amount of time. Accordingly, this can address doubts about the responsible party when there are various stakeholders involved in product development.
Taxes or Fees	**0**	**3**	**4**	**7**	Taxing or charging low efficient buildings, such as CO2 cost, was identified as a financial incentive enabling the widespread application. It has been perceived to be linked to the effect of changes in energy policies in the widespread application.
Ability to Compete Traditional Systems	**0**	**5**	**2**	**7**	The ability of façade systems integrating such technologies to compete traditional systems in terms of cost and/or performance was perceived as a key enabling factor. Such enabling factor was considered to be clarified to designers during early design stages. The ability to demonstrate such factor can have a vital role in increasing the interest of clients and developers.
Circularity	**0**	**0**	**7**	**7**	The ability of façade products integrating such technologies to incorporate the concepts of circular economy has been perceived to be a key factor to be considered in both of design as well as end of life phases. However, majority of interviewees mentioned it when discussing key aspects to consider for the end of life, such as the case of reusability and recyclability.
Fire Resistance	**2**	**0**	**5**	**7**	The ability of such façade products to be fire-resistant, such as involving the use of non-combustible materials, has been perceived to support the widespread application. Such factor has been considered to be taken into account for building regulations as well as in standards and guidelines for stakeholders involved in early design stages.
Ability to be Combined and Interact with Other Systems	**3**	**0**	**4**	**7**	The ability to of such products to be combined and interact with other systems, such passive strategies or any other technologies, in order to achieve proper energy performance was perceived to be a key factor to be considered during the design phase.
Clear Design Boundaries	**0**	**0**	**6**	**6**	The possibility to have clear design boundaries for architects has been perceived to be a key enabling factors, where architects are aware of the area where they have some design freedom, such as changeable parameters, and others which have some bounds or limitations, such as fixed parameters. Such factor has been linked to the design and production phases as well as has been perceived as an element to be considered in standards or guidelines for architects or engineers.
A Relevant Type of Building Ownership	**0**	**0**	**6**	**6**	A relevant type of building ownership tends to be a key factor supporting the widespread application of SCIFs. Although it depends on the nature of project, having one client who is the building user at the same time was considered to be more relevant than having multiple owners and tenants in the buildings, such as in the case of apartment buildings. This is due to the fact that having multiple owners and tenants may require convincing every owner or tenant as well as arranging separate invoices. Such enabling factor has been linked to both of design and operation phases, since type of building ownership and its operation should be identified from early phases.
Project Total Budget	**0**	**3**	**3**	**6**	The ability to stay within the total project budget, or specified budgets to be spent per floor area, has been perceived to be a key enabling. This is due to the fact that it has a direct effect on the applicability as well as developing affordable and financially feasible facade products. Such factor depends on the nature of the project, such its size. It has been perceived to be considered during early design stages at which various stakeholders should be involved. Higher budget projects tend to be a key motivating factor supporting the application.

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Table C.1 (*continued*)

Enabling Factor	Frequency				Interpretation and Description
	T&P	F	P&S	Total	
Less Interactions by Users	**0**	**0**	**6**	**6**	The ability to have products requiring minimum amount of interactions by users during the operation phase has been perceived as a key factor supporting the widespread application.
Durability and Long Life Span of Components	**3**	**0**	**3**	**6**	The ability of façade products integrating a particular technology to have longer life spans, for example 20–50 years, has been perceived to address concerns related to the potential difference in life spans of components, such as when the integrated technology has a shorter life expectancy than the main facade. Such factor has been considered to be taken into account during the production phase, such as performing durability tests, to ensure the durability and long life span of components during the operation phase.
Design for Manufacturing and Assembly	**0**	**1**	**5**	**6**	Designing products for manufacturing and assembly has been perceived to support the development of affordable and financially feasible facade products. Such factor takes into account various aspects that include stakeholders welling to implement designed products, potential extra time for production and assembly, as well as potential risks related to defects or failures in products. Such factor has been linked to the design and production phases where different stakeholders, such as production and construction companies, can be involved so that information related to the production as assembly tools and technologies is clear during early stages.
Waterproofing/tightness	**4**	**0**	**2**	**6**	Waterproofing/tightness of such façade products has been perceived to be a key factor to be considered in standards and guidelines for stakeholders involved in early design stages.
Product as a Service/Leasing Construction	**0**	**3**	**2**	**5**	Delivering façade products as a service has been perceived as a financial incentive, since it can minimize the high initial investment costs for building owners. Having a product as a service has been identified to be considered to be one of the key roles to be taken into account by system suppliers to convince other stakeholders, such as clients, during the design phase.
Certified Products	**0**	**0**	**5**	**5**	Having certified products has been perceived to be a motivating factor supporting the widespread application. It has been linked to the effect of changes in building regulations in the widespread application. Furthermore, it has been identified as one of the key aspect to be available during the design phase. Although product certification has been identified as an enabling factor, interviewees 8 and 14 have some concerns that are related to the costs and potential difficulties associated with the certification process.
Ability to Upgrade	**1**	**0**	**4**	**5**	The ability to upgrade such façade products has been perceived as a key factor to be considered for the maintenance and durability. It takes into account changing parts in order to extend the service life. This factor has been identified to be considered during both of the operation and end of life phases.
Similarities in systems working principles	**3**	**0**	**1**	**4**	The ability of various products to have similarities in their core working principles has been identified as an enabling factor. Such factor can help in achieving mass customization, such as in the case of the automobile industry. It has been perceived to attract designers and clients to apply such technologies. This factor has been perceived to be considered in the production phase, so that manufacturers are able to demonstrate easily the working principles of different products or technologies to designers and clients.
Clear and Simple Guidance	**0**	**0**	**4**	**4**	The ability to have a clear and simple guidance, such as IKEA instructions as mentioned by interviewees 10 and 21, for the required workforce during assembly phase has been perceived to be a key enabling.
Low Waste	**0**	**0**	**4**	**4**	The ability of such façade products to generate minimum amount of waste at their end of life phase has been considered to be a key enabling factor.
Industrialization	**0**	**2**	**1**	**3**	Having industrialized systems has been perceived to be a key factor supporting the development of affordable and financially feasible facade products. Such systems has been identified to be considered in the production phase in order to minimize on-site works.
Adaptable to multiple cases and conditions	**1**	**0**	**2**	**3**	The ability of such façade products to be applied at different cases, such as different buildings uses, has been perceived to support the widespread application. Such factor has been linked to the design and production phase, where aspects related to the building use, climate and ambient conditions are taken into account.
Nontoxic Materials	**1**	**0**	**2**	**3**	Avoiding the use of toxic materials in such façade products has been perceived to enable the widespread application. It has been linked to design, production, as well as end of life phases.
Weight and Structural Safety	**2**	**0**	**1**	**3**	The safety of the additional weight of integrated technologies into façades, especially in existing buildings, has been perceived as a key factor to be considered during the design phase.
No moving parts	**2**	**0**	**1**	**3**	Having static façade systems that do not have moving parts has been perceived as key factor to be considered to avoid product complexities in terms of maintenance requirements. Such factor can support achieving low maintenance during operation phase.
Integrated by Calculation Software Packages	**0**	**0**	**2**	**2**	The ability of such façade products to be integrated by calculation software packages used in the design phase has been perceived as a motivating factor that increase the interest in the application of such technologies.

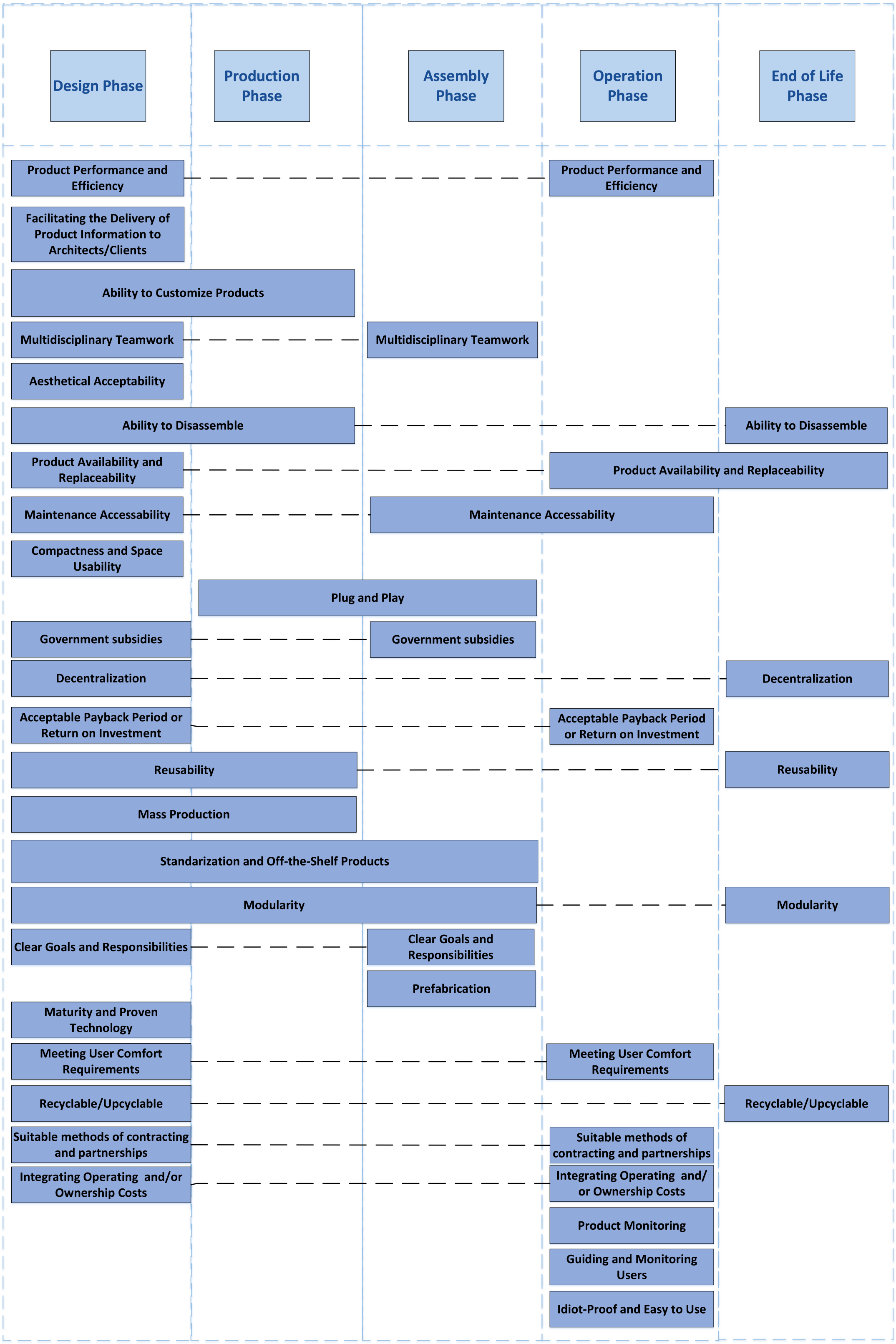

Fig. C.1. Mapping the enabling factors in the façade design and construction process (Part 1).

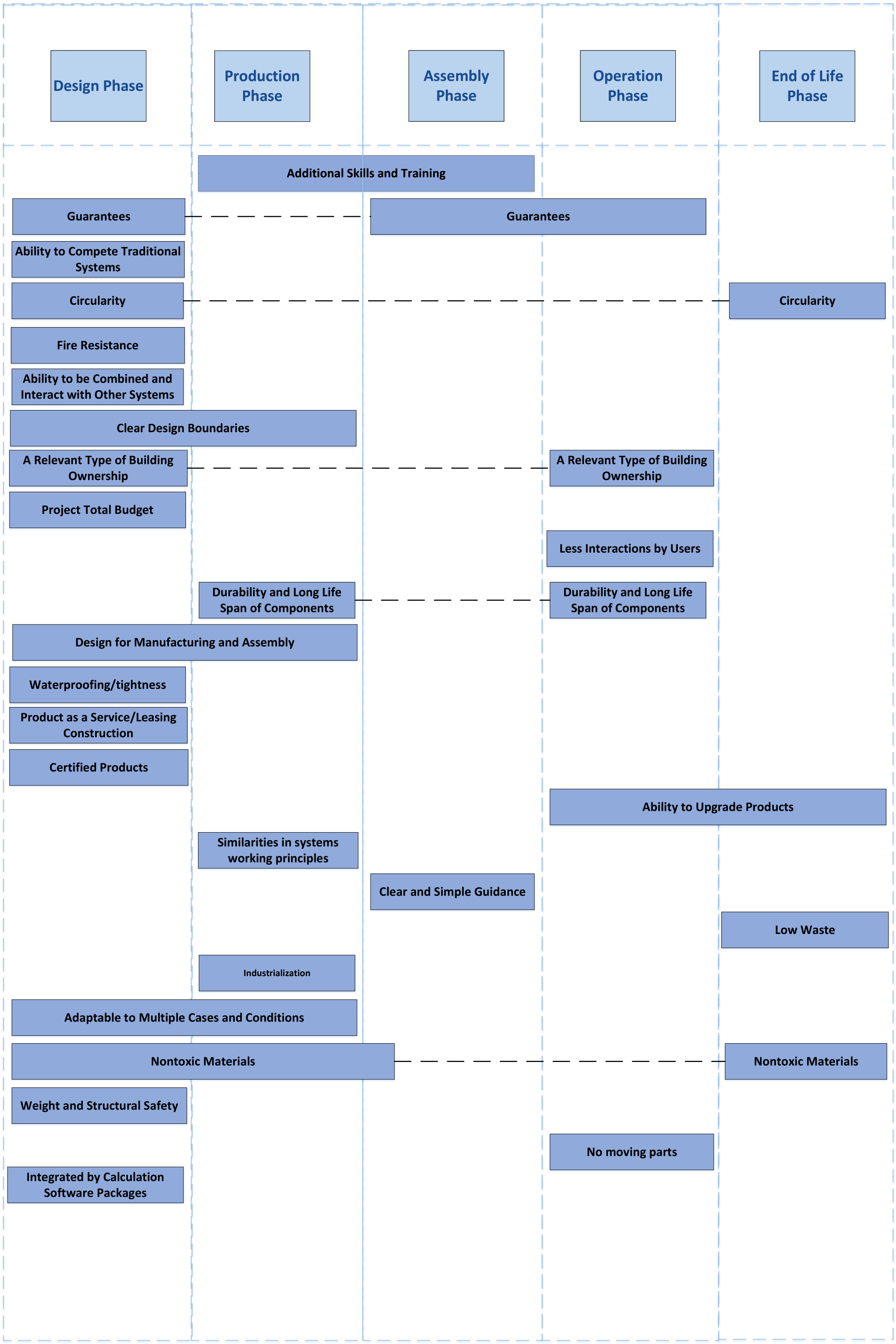

Fig. C.2. Mapping the enabling factors in the façade design and construction process (Part 2).

References

[1] G. Sahin, F.V. Ayyildiz, Chapter 14: climate change and energy policies: European union-scale approach to a global problem, in: H. Qudrat-Ullah, M. Asif (Eds.), Dyn. Energy, Environ. Econ. A Sustain. Perspect., Springer Nature Switzerland AG, 2020, pp. 295–320.
[2] M. Santamouris, Cooling the buildings – past, present and future, Energy Build. 128 (2016) 617–638.
[3] N. Enteria, T. Sawachi, Air conditioning and ventilation systems in hot and humid regions, in: N. Enteria, H. Awbi, M. Santamouris (Eds.), Build. Hot Humid Reg. Hist. Perspect. Technol. Adv., Springer Nature Singapore Pte Ltd., 2020, pp. 205–219.
[4] IEA, Global Air Conditioner Stock, 2019, pp. 1990–2050. https://www.iea.org/data-and-statistics/charts/global-air-conditioner-stock-1990-2050. (Accessed 15 November 2021).
[5] IEA, Cooling, Int. Energy Agency. (2020). https://www.iea.org/reports/cooling. (Accessed 27 October 2021).
[6] G.N. Tiwari, A. Tiwari, Shyam, solar cooling, in: Handb. Sol. Energy. Energy Syst. Electr. Eng., Springer, Singapore, 2016, pp. 471–487, https://doi.org/10.1007/978-981-10- 0807-8_11 G.
[7] I. Sarbu, C. Sebarchievici, Solar Heating and Cooling Systems: Fundamentals, Experiments and Applications, Academic Press, 2016.
[8] A. Prieto, U. Knaack, T. Auer, T. Klein, Solar coolfacades: framework for the integration of solar cooling technologies in the building envelope, Energy 137 (2017) 353–368.
[9] D. Neyer, D. Mugnier, A. Thür, R. Fedrizzi, P.G. Vicente Quiles, Solar Heating and Cooling & Solar Air-Conditioning, IEA Solar Heating and Cooling Technology Collaboration Programme, 2018.
[10] A. Alahmer, S. Ajib, Solar cooling technologies: state of art and perspectives, Energy Convers. Manag. 214 (2020), 112896.
[11] A.S. Alsagri, A.A. Alrobaian, S.A. Almohaimeed, Concentrating solar collectors in absorption and adsorption cooling cycles : an overview, Energy Convers. Manag. 223 (2020), 113420.
[12] W. He, X. Zhang, X. Zhang, Solar heating, cooling and power generation—current profiles and future potentials, in: X. Zhao, X. Ma (Eds.), Adv. Energy Effic. Technol. Sol. Heating, Cool. Power Gener., Springer Nature Switzerland AG, 2019, pp. 31–78, https://doi.org/10.1007/978-3-030-17283-1_2.
[13] S. Karellas, T.C. Roumpedakis, N. Tzouganatos, K. Braimakis, Solar Cooling Technologies, CRC Press, 2019.
[14] A. Prieto, U. Knaack, T. Auer, T. Klein, Feasibility study of self-sufficient solar cooling fa ade applications in different warm regions, Energies 11 (2018), 121693718.
[15] W. Laufs, E. Verboon, Chapter 10: innovative façade design and products, in: A.M. Memari (Ed.), Curtain Wall Syst. A Prim., American Society of Civil Engineers, Reston, Virginia, 2013, pp. 154–193.
[16] Y. Ibraheem, P. Piroozfar, E.R.P. Farr, Integrated façade system for office buildings in hot and arid climates: a comparative analysis, in: M. Dastbaz, C. Gorse, A. Moncaster (Eds.), Build. Inf. Model. Build. Performance, Des. Smart Constr., Springer, Cham, 2017, pp. 273–288.
[17] P. Bonato, M. D'Antoni, R. Fedrizzi, Modelling and simulation-based analysis of a façade-integrated decentralized ventilation unit, J. Build. Eng. 29 (2020), 101183.
[18] A. Prieto, T. Klein, U. Knaack, T. Auer, Main perceived barriers for the development of building service integrated facades: results from an exploratory expert survey, J. Build. Eng. 13 (2017) 96–106.
[19] H. Hamida, T. Konstantinou, A. Prieto, T. Klein, U. Knaack, Solar cooling integrated façades: main challenges in product development for widespread application, in: CLIMA 2022 14th REHVA HVAC World Congr., 2022. Rotterdam, the Netherlands.
[20] Y. Jabareen, Building a conceptual framework: philosophy, definitions, and procedure, Int. J. Qual. Methods 8 (2009) 49–62.
[21] PMI, A Guide to the Project Management Body of Knowledge (PMBOK Guide), sixth ed., Project Management Institute (PMI), Newtown Square, Pennsylvania, 2017.
[22] U. Knaack, T. Klein, M. Bilow, T. Auer, Façades: Principles of Construction, second ed., Birkhäuser, 2014.
[23] A. Prieto, U. Knaack, T. Auer, T. Klein, COOLFACADE: state-of-the-art review and evaluation of solar cooling technologies on their potential for façade integration, Renew. Sustain. Energy Rev. 101 (2019) 395–414.
[24] A. Prieto, U. Knaack, T. Auer, T. Klein, Solar façades – main barriers for widespread façade integration of solar technologies, J. Facade Des. Eng. 5 (2017) 51–62.
[25] J.F. Azcarate-Aguerre, T. Klein, A.C. den Heijer, R. Vrijhoef, H.D. Ploeger, M. Prins, Drivers and barriers to the delivery of integrated Façades-as-a-Service, Real Estate Res. Q. 17 (2018) 11–22.
[26] T. Klein, Integral Facade Construction: towards a New Product Architecture for Curtain Walls, Delft University of Technology, 2013.
[27] A. Prieto, T. Armijos-moya, T. Konstantinou, Renovation process challenges and barriers: addressing the communication and coordination bottlenecks in the zero-energy building renovation workflow in European residential buildings, Archit. Sci. Rev. ISSN. (2023), https://doi.org/10.1080/00038628.2023.2214520.
[28] A. Hauashdh, J. Jailani, I. Abdul Rahman, N. Al-fadhali, Strategic approaches towards achieving sustainable and effective building maintenance practices in maintenance-managed buildings: a combination of expert interviews and a literature review, J. Build. Eng. 45 (2022), 103490.
[29] F.J. Ying, N. Zhao, J. Tookey, Achieving construction innovation in best value procurement projects: New Zealand mega projects study, Construct. Innovat. (2021) 1471–4175, https://doi.org/10.1108/CI-11-2020-0182.
[30] M. Hennink, I. Hutter, A. Bailey, Chapter 6: In-Depth Interviews, in: Qual. Res. Methods, SAGE Publications Ltd, London, UK, 2011, pp. 108–131, https://doi.org/10.4135/9781412963909.n238.
[31] L.N. Groat, D. Wang, Architectural Research Methods, second ed., Wiley, 2013.
[32] J.W. Creswell, J.D. Creswell, Research Design: Qualitative, Quantitative, and Mixed Methods Approaches, fifth ed., SAGE Publications, Inc, 2018.
[33] S. Durdyev, M. Ashour, S. Connelly, A. Mahdiyar, Barriers to the implementation of building information modelling (BIM) for facility management, J. Build. Eng. 46 (2022), 103736.
[34] S.O. Ajayi, L.O. Oyedele, O.O. Akinade, M. Bilal, H.A. Owolabi, H.A. Alaka, K.O. Kadiri, Reducing waste to landfill: a need for cultural change in the UK construction industry, J. Build. Eng. 5 (2016) 185–193.
[35] A. Bryman, Social Research Methods, fifth ed., Oxford University Press, 2016.
[36] R. Fellows, A. Liu, Research Methods for Construction, fourth ed., John Wiley & Sons, Ltd, 2015.
[37] D.W.M. Chan, T.O. Olawumi, A.M.L. Ho, Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: the case of Hong Kong, J. Build. Eng. 25 (2019), 100764.
[38] A.T.L.A.S. ti, Interview Analysis that Helps You Leverage Every Piece of Data, 2023. https://atlasti.com/interview-analysis-tools. (Accessed 6 March 2023).