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Design and Manufacturing of Adaptive Facades in a Life Cycle Approach: A Survey on Challenges and Solutions in the Italian Building Industry

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Abstract: The market of Adaptive Building Skins has been growing at a slow but incremental speed, as these technologies ensure better indoor climatic comfort and more efficient energy management than traditional solutions. Nonetheless, if we acknowledge the building as a system of physical qualities oriented to overall environmental performance, the resource optimization has to be extended to considering a wider range of environmental impacts along the entire building life cycle. For this purpose, the Life Cycle Assessment (LCA) method is recognized by stakeholders as the most world-renowned standardized tool for weighting environmental impacts. The aim of this study is to scrutinize the state of the art of LCA among stakeholders enrolled in the design and manufacturing of building and adaptive facades in the Italian market. Data have been collected throughout interviews and an online survey focusing on investigating the knowledge and experience level of participants. Results not only draw the attention to develop new market models by implementing sustainable building protocols concerning adaptive technologies, but also provided a positive assessment on the usability degree of a parametric design mapping based on a systemic and life-cycle-oriented approach to achieve environmental scopes and introduce competitive factors and boost innovation in the Italian building industry.

Keywords: adaptive facades; Life Cycle Assessment; building technologies; adaptive; systematic; mapping; sustainable architecture; design parameter; survey

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) stated that one of the available pathways to limit global warming to 1.5 °C above pre-industrial levels is that global carbon emissions need to fall to 45% from 2010 levels by 2030 and continue a steep decline to zero net emissions by 2050 [1]. A sector which addresses this reduction's process is the building construction and operations, which accounted for 36% of global final energy use and 39% of energy-related carbon dioxide (CO_2) emissions in 2017 [2].

In 2018, the Board of the European Investment Bank approved the Smart Building Initiative, intending to make investments in energy efficiency projects in residential buildings. The 2018/844 Energy Performance of Buildings Directive (EPBD) on the energy performance of buildings recommends the adoption of "smart" indicators to measure the building's capacity to use intelligent devices to adapt the operations to the occupants' needs and to improve the energy efficiency and the overall performance [3]. Undoubtedly, these goals and strategies suggest the spreading use of adaptive building skins technologies, indeed, the terms "Smart" and "Intelligent" have been investigated by many authors with reference to adaptive envelopes [4–7].

In this context, in which it is expected that the technological development of adaptive façade solutions acquires a significant market share in the next years, it is of the utmost significance to investigate the real effectiveness in maintaining simultaneously indoor environmental comfort and building energy efficiency [8]. Nonetheless, if we acknowledge

the building as a system of physical qualities oriented to environmental performances, the resource optimization has to be extended to considering a wider range of environmental impacts along the entire building life cycle. Being nothing less than the materials used in building construction, they account for 28% of the annual "buildings related" CO_2 emissions [2]. For this purpose, stakeholders recognize the Life Cycle Assessment method as the most reliable standardized tool for weighting building environmental impacts. Nevertheless, recent studies have still highlighted stakeholders' difficulties in modelling scenarios, and finding estimated default values for building parts or components, as the most important knowledge gaps in the phase of "screening building LCA", when the possibilities of savings increase as long as more knowledge on building performance is acquired [9,10].

The outcome to be drawn from these premises is the need for a systemic and parametric framework to orientate stakeholders in LCA-related design and avoid problem-shifting in posterior life cycle stages; even more, if we consider some distinctive attributes of adaptive facades [11]. Indeed, while reducing the building energy consumption during the operational phase, these technologies have the potential to produce repercussions on environmental impacts in the cradle-to-gate phase, being characterized either by new generation materials, whose impacts are often still little known, or by complex facade mechanisms, which require a laborious assessment. Moreover, the dynamic features of these technologies impact on the maintenance, repair and replacement cycles of facade systems having a reduced service life compared to traditional elements.

Unquestionably, the LCA approach is not to be meant neither as a constraint nor as the only concerning issue with regards to design. Building technology is always conceived taking into account multiple problem-solving factors of architecture, other than environmental impacts, such as safety, security, aesthetic quality, indoor environmental quality, economic sustainability. Despite that, this study should be intended as a focus on a specific topic of the adaptive facade design, and other elements than environmental quality to consider would be out of the research scope.

LCA Mapping of Adaptive Façades

The systemic and parametric approach is also supported by the growing application of Building Information Modeling (BIM), a methodology built on the integration and connection of different aspects and stakeholders for complex decision-making. As highlighted by a number of studies, digital computation plays a strategic role in exploring design solutions in which form generation, dynamic building performance simulations, and on-site processes are shaped in a single workflow [12–14]. Furthermore, as BIM software is built as object-oriented, a parametric approach allows for the generation of numerous but systematic design alternatives implemented manually or by computational optimization tools [15]. Although most of the parametric building materials database integrated into BIM tools do not yet contain environmental data [16,17], a few LCA integrated tools have been developed in recent years (plug-ins as One Click LCA, Tally) [18,19]. Through 3D modelling and a choice of materials and components, the building's environmental impact can be calculated in real time. As a further example, Bombyx is an open-source plug-in for Grasshopper 3D, a parametric design software based on Rhinoceros 3D [20]. Aside from software development, research has also explored the possibility of mapping parameters that affect environmental impacts in the form of an information flow matrix called Architecture of Variables (AoV) [21,22].

In the same framework of methodologies for the integration between BIM and LCA, a systemic approach has been considered more appropriate to define a mapping of design parameters addressed to adaptive facades technologies [23,24]. This tool prompts the creative and exploratory process analysing the interconnections of design variables, along the life cycle stages, and observing the complexity of these building skins, illustrating their multiple functions and sustainability performances.

At present, examples of built adaptive facades are made with products on the market, but most of the adaptive technologies are research prototypes ([11,25–27] Ghosh et al. 2020 [28]). The evolution of adaptive facades, closely linked to the concept of performance, is oriented to develop Biomimetic Adaptive Building Skins (Bio-ABS), a technology that responds to environmental conditions by changing its morphological or physiological properties or behaviour over time, translated from biological models to meet variant functional requirements of a building to improve its overall performance (Kuru et al. 2019 [29]). Among this typology, Bio-ABS can be either responsive systems, which are based on materials properties having the ability to reconfigure themselves if subjected to external stimuli [30–32], or control systems with dynamic and configurable parts acting at the macro-scale or micro-scale [8,33,34].

Furthermore, following this research stream, several studies were conducted to creating effective design tools for the built environment such as "BioSkin", "Towards the living envelope" and "Architecture follows nature" (Al-obaidi et al. 2017 [35]). Nevertheless, new design tools should be developed to include multidisciplinary contributions for enhancing multiperformance of adaptive and nonadaptive Bio-Building Skins (Cruz et al. 2021 [36]).

The scope of this article is twofold. In the first place, the analysis is focused to collect data to share and disseminate the miscellaneous perspectives of the different stakeholders. Secondly, it provides a basis to implement a design and methodological parametric mapping based on a systemic and life-cycle-oriented approach for the Life Cycle Assessment of adaptive facades.

2. Materials and Methods

The analysis was conducted upon the information obtained from stakeholders in the Italian sector of sustainable buildings. The survey was disseminated using different media to increase visibility (mailing lists, social networks). The interviewees were also contacted by telephone and e-mail, inviting them to consult the mapping uploaded online and responding directly online.

The information was collected through an electronic survey, created with the online tool Survey Monkey [37] in the form of a semi-structured interview with a combination of single-selection, multiple-choice questions, free textbox questions. Most of the multiple-choice questions were semi-closed since they also included a textbox where respondents could provide information beyond the pre-defined response categories.

The questionnaire has 45 questions, arranged in 6 sections, and it started with a welcome page that briefly explains the purpose, structure and duration of the survey, the procedures to be followed as well as that the survey is voluntary and confidential.

The six sections are:

- "Participant's general information (part 1–part 2)"—on the location and type of activity and about experiences on sustainability, life cycle assessment or life cycle thinking as well as adaptive facade design (*Part 1*: Questions 1–7 and *Part 2*: Questions 15 and 16). Further open questions are provided to those who had a background on these topics to assess their knowledge degree. (*Part 1:* Questions 8–14 and *Part 2:* Questions 17–22);
- "Knowledge gaps and issues in building LCA"—this part is intended to identify how life cycle assessment is valued in the context of the activity carried out and the critical issues encountered in its use (Questions 23–28);
- "Issues on design and manufacturing of adaptive facades"—this section aims to obtain cross-cutting information regarding the sphere of influence of the Life Cycle assessment for early design goals and concerning the different life cycle phases of the adaptive envelope (Questions 29–33);
- "Evaluation of the usability of the LCA design tool"—these questions aim to explore design benefits in synergy with a list of general objectives and the degree of user-friendliness of the mapping. The interviewee is allowed to consult the online mapping's graphics (Questions 34–42);

- "Survey publication and eventual involvement"—this section concerns further comments and recommendations and insights for future research, as well as for declarations of responsibility for the information collected (Questions 43–45).

The answers were analysed as a whole and summarized in text and graphics. The following stakeholders were interviewed: architects/engineers, design companies, external consultants (sustainability certifications), designers/manufacturers of systems, components, materials for adaptive facades, construction companies, facilities managers, academic researchers.

The main constraints of this study are represented by the short time interval in which the interviews were conducted and the few bibliographical references of similar studies in other countries [10,38,39]. Another constraint was given by the risk of misleading interpretations which were significantly reduced thanks to telephone calls and face-to-face interviews. Nonetheless, the questions refer to extensive European research of the 7th Framework Program, conducted on the harmonization and use of the LCA in the design and decision-making processes [40].

3. Results

A total of 45 stakeholders were reached through a web link and by direct e-mail invitation, of which 29 have shown interest in participating. In consideration of the addressed issue, which is still considered a business "niche", and in comparison with similar surveys carried out in other countries [10,38,39,41,42], the feedback obtained in terms of participation is positively assessed. It should be noted that, in the case of multiple-choice questions, the number of results does not correspond to the number of respondents.

3.1. Participant's General Information (Part 1)

In the first two parts of the questionnaire, data on the location and the type of activity carried out by the interviewee have been collected, as well as information on knowledge and experiences in the field of environmental certifications and life cycle tools. This first picture facilitates the understanding of the participants' approach in responding to the next sections on "Knowledge gaps and issues in building LCA and Evaluation on the usability of LCA design mapping".

The majority of respondents (48%), who mainly carry out their activities in Central and Northern Italy (North 65%, Centre 72%, South and islands 17%) (Q.1 and Q.2) work in design firms (including external consultancy activities, design/installation of HVAC systems and lighting and facilities managers). Around 21% of interviewees belong to the academic research field and 28% of respondents are manufacturers of systems and/or components and/or materials for adaptive facades, who also carry out design and research activities within the company. The remaining 3% are distributed among the various categories of activities presented in the multiple-choice question (*What type of company do you represent?* Q.4). The answers are shown in Figure 1. Property managers and investors did not respond to the survey.

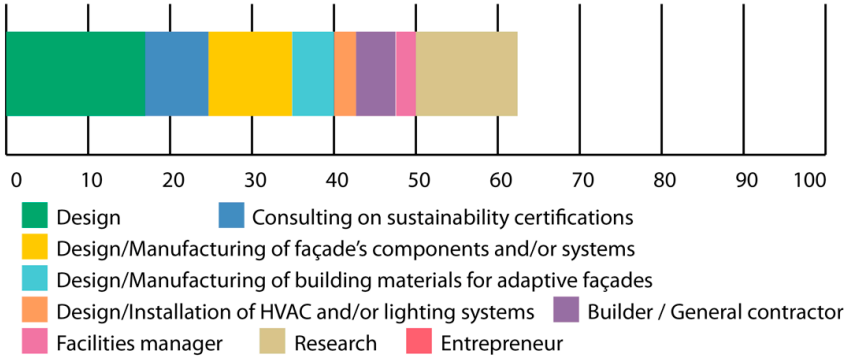


Figure 1. Q.4. What type of company do you represent? (multiple-choice).

When asked about the level of knowledge in the field of environmental certifications (Q.5 and Q.6) and Life Cycle tools (Q.7), 76% of participants interviewed have at least a direct or indirect experience and the most pursued sustainable certification protocol is Leadership in Energy and Environmental Design (LEED) (46%). Concerning the experience with Life Cycle-type tools, 17% commissioned their use or collaborated with a certifying body, while 24% carried out directly an LCA assessment. The "Other" answers also denote an interest and a basic knowledge among the remaining respondents, although they did not participate in practical applications (Figure 2).

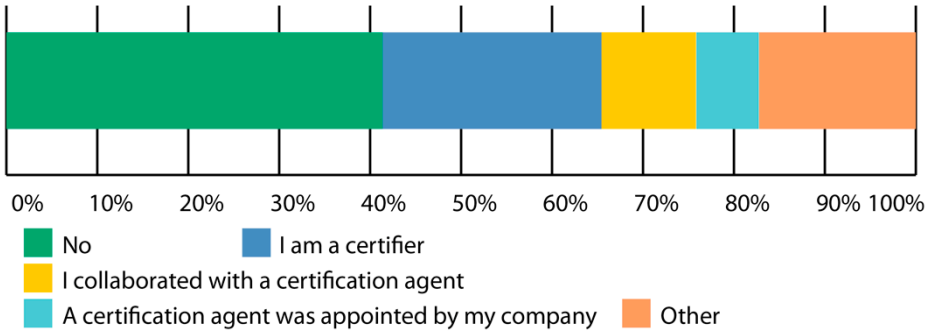


Figure 2. Q.7. Do you have experience with life cycle thinking tools and/or LCA?

The open questions, in which it was possible to list the characteristics of the LCA carried out (Q.8, Q.9), showed that the offices and commercial buildings are the most assessed building typologies, as these kinds of evaluations are often appointed in the context of sustainability certifications to increase the visibility of the real estate investment. Other examples of applications concern synergies between academia and manufacturers' goals (up to 50%) for the design development of component's facades. In that case, the overall feedback about the impact of LCA on the final design is positive, highlighting a cascade effect on the environmental impacts of the production chain (Q.10). The LCA scale of application (Q.11) is shown in Figure 3. Among the indicators analysed, *Resource consumption* is a relevant topic followed by other quantitative and qualitative assessing parameters such as *Energy consumption*, CO_2*eq emissions*, *Volatile Organics Compounds*, material reuse, locally sourced materials, traceability of raw materials (Q.12, Q.13). The input data sources for LCA are represented by databases (Eco Invent, One Click LCA), literature (e.g., the German Sustainable Building Council (DGNB)) or technical specifications provided by the customer (material sheets and product certifications) (Q.14).

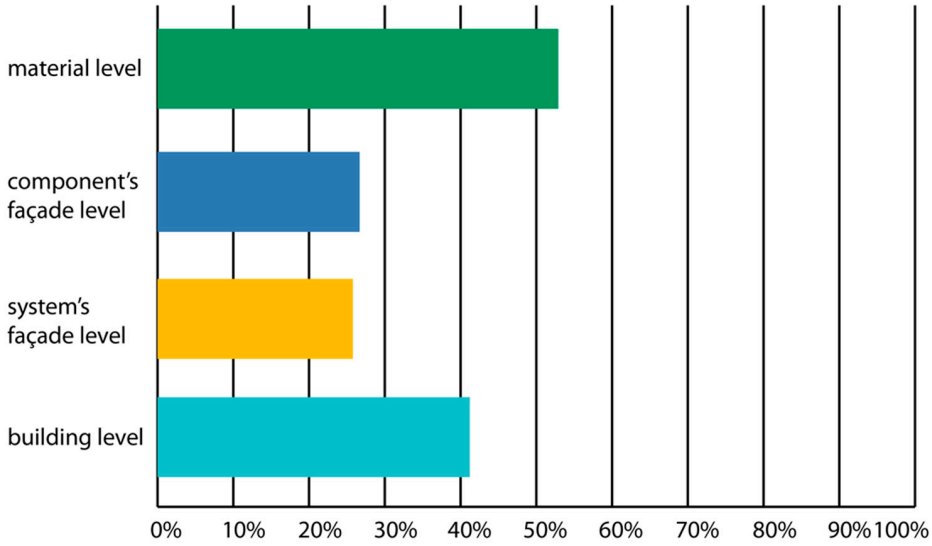


Figure 3. Q.11. At which level was the LCA carried out?

3.2. Participant's General Information (Part 2)

Single-selection, multiple-choice and open-ended questions were addressed to examine the degree of participant's experience in the design and construction of adaptive facades (design stage, type, and size of the building to which the application of adaptive facades is addressed and the level of innovation achieved) (Q.15–Q.17) (Figures 4 and 5). Among respondents operating in facade systems, applications on high-rise office and residential buildings prevail, although studies have mainly been carried out at the design level or prototypes have been made on a 1:1 scale. The level of innovation is considered medium to high. All the interviewees who had experience on the theme of adaptive envelopes answered open questions related to a proposed classification of adaptive building skins (Q.18–Q.22) [43]. The answers have been reported in a re-elaboration of the scheme (Figure 6) and cloud graphs (Figures 7–10).

Mainly, it should be pointed out that up to 20% of the interviewees did not agree with the proposed acronyms or terminologies, but posed the need to specify them with an alternative text, then reinterpreted by the author and included in the schemes. About the scheme on *Summary of the connections between environmental agents and ABSs final goals*, strongly based on a biomimetic design approach, there was an absence of correspondence between the content of the scheme and the terms used to answer. On the other hand, the questions from Q.18 to Q.22 have been formulated without predetermined options to understand the readability and usability of the proposed schemes.

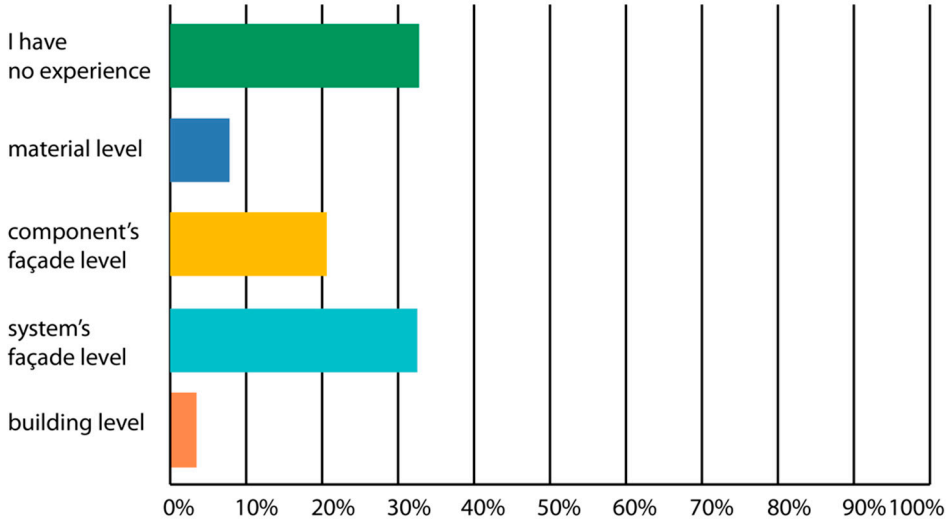


Figure 4. Q.15 On which level do you have experience with the design/construction of adaptive facades? (multiple choice option).

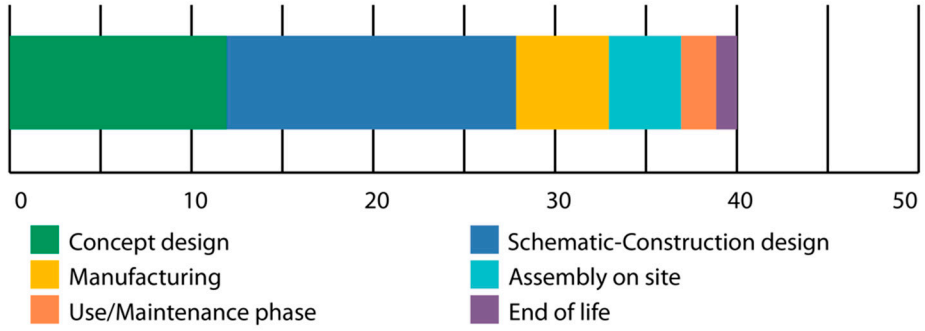


Figure 5. Q.16 In what phase are you working in the field of traditional/adaptive facade? (multiple-choice option).

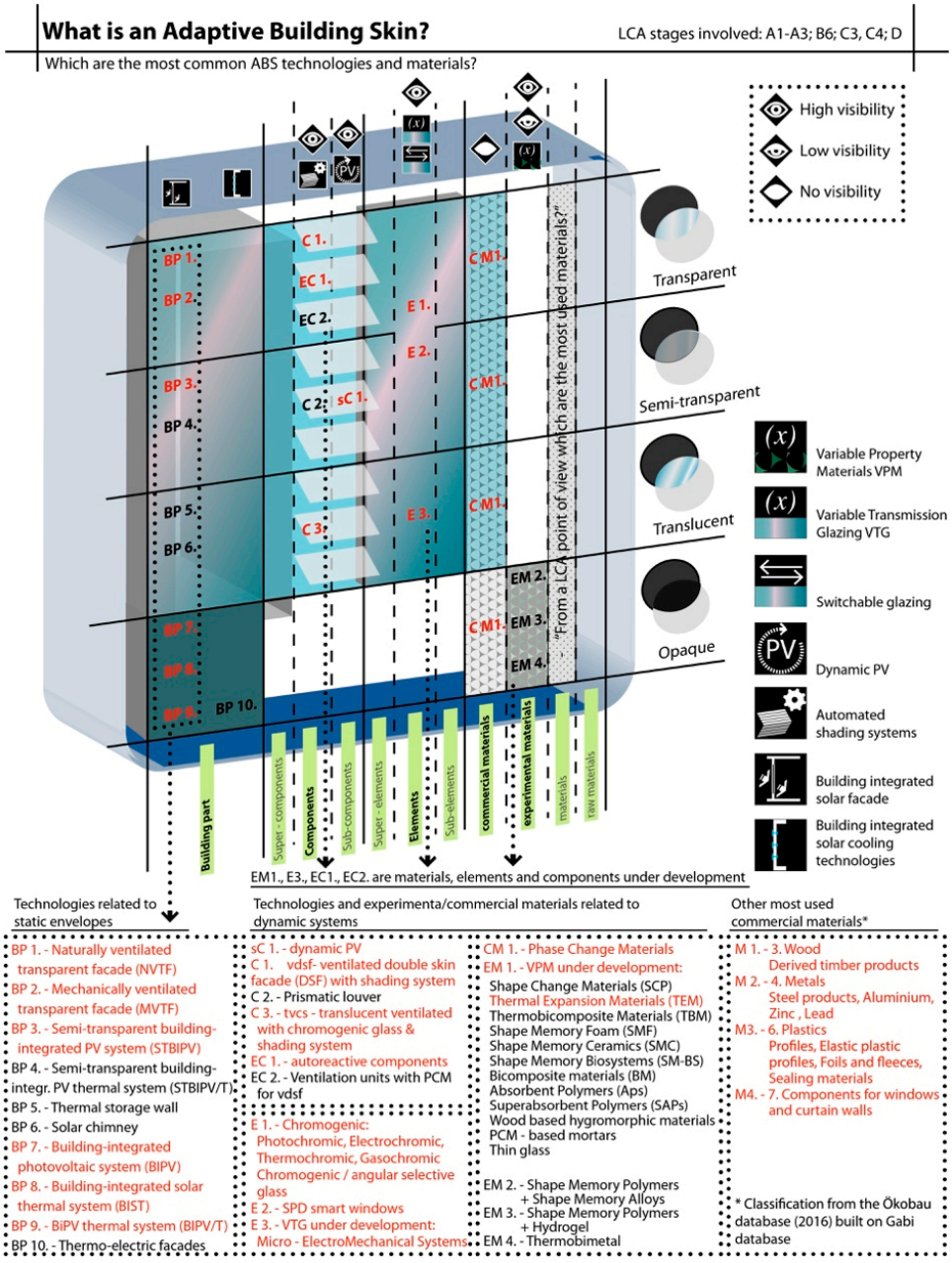


Figure 6. Systematic illustration of the typologies of ABSs, which classified the most widespread technologies and materials [Reprinted with permission from ref. [43] Copyright 2019, Copyright M. Crespi, Sandra G.L. Persiani]. In red, the typologies used among the respondents. Q.18. If you have had experiences with design/construction of adaptive facades, with reference to Figure 1, which components/elements/materials identify the adaptivity?



Figure 7. Q.19. If you have had experiences with the design/construction of adaptive facades, with reference to Figure 2, at which scale of the building skin was the adaptivity integrated? (component/element/material)?



Figure 8. Q.20. If you have had experiences with the design/construction of adaptive facades, with reference to Figure 3, how does the adaptation work (autoreactive, connected to a Building Automation System)?



Figure 9. Q.21. If you have had experiences with the design/construction of adaptive facades, with reference to Figure 4, within which timeframe did the adaptive processes occur (days, hours, minutes, seconds)?



Figure 10. Q.22. If you have had experiences with the design/construction of adaptive facades, with reference to Figure 5, why was adaptivity introduced (energy efficiency, indoor environmental quality…)?

3.3. Knowledge Gaps and Issues in Building LCA

About 70% of those interviewed answered this section. The comparison between the questions on the importance of the environmental assessment of the life cycle of buildings for the activity carried out (Q.23) and for the overall sustainability of the buildings (Q.24) shows that, if in all respondents the LCA is considered almost very important for the sustainability of buildings, 30% of them do not believe that in their business this method can be of great use. Thus, it has to be related to the type of activity carried out (e.g., research in other fields, design only).

Figure 11 shows the results relating to the most widespread knowledge gaps in the field of life cycle assessment of buildings, and, in particular, of adaptive facades (Q.25), which are, predominantly, the absence of input data for some products (58%) and the lack of knowledge on environmental benefits in the maintenance/repair stage (53%) and in the recycling/reuse at the end of life (53%). This result corresponds to the life cycle phases of adaptive facades, which, according to the interviewees, have the greatest lack of data and guidelines: use phase (117%) and end of life (50%) (Q.26). In addition, 72% of respondents believe that the factor that hinders the assessment of the life cycle of adaptive facades is the

difficulty in obtaining data (Q.27). The reasons beyond the possible obstacles in using LCA results are comparability (37%), transparency (26%) and lack of adequate knowledge for the evaluation of the results (32%). An interviewee highlighted how the difficulty lies in the absence of cultural preparation by investors who do not have sustainable and long-term market models capable of guaranteeing a return on short-term investments (Q.28).

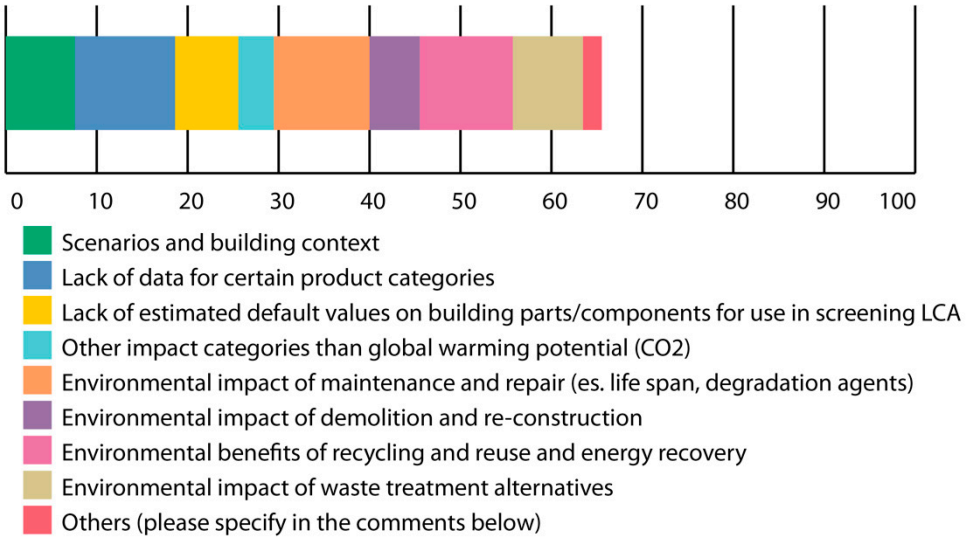


Figure 11. Q.25. In your opinion, what are the most important knowledge gaps in building LCA, and specifically in adaptive facade LCA? (multiple-choice option).

3.4. Issues on Design and Manufacturing of Adaptive Façades

The answering rate of these questions' group (Q.29–Q.33) is the same group above (Q.23–Q.28). From a comparison between the activities carried out by the interviewees and the responses of Section 3, there are no substantial differences by type of activity. Among the factors that influence the design and construction of adaptive facades, there is no predominant one. However, energy performance and environmental impact sum up 71% of the choices (Q.29) (Figure 12). Among the possible scenarios for the life cycle assessment of adaptive facades, the choice is addressed to facade lifespan and the maintenance and operating scenarios (Q.31) (Figure 13). The cross-analysis of the answers Q.25, Q.26, Q.29 and Q.31 shows a consistency in the results aimed at highlighting the importance of collecting input data on the lifespan of adaptive facades, in particular, concerning the use phase (maintenance and repair), to which the attention of most of the interviewees is addressed. The difference between the early design goals (energy performance and indoor environmental comfort) and the LCA objectives (environmental impacts of the maintenance and repair phases) is also underlined, which implies an interest in new aspects of innovation and competitiveness in the adaptive building skins market. Indeed, innovation (43% Q.29) and cost (38% Q.29) are two influencing factors related to technology, which characterizes the design of adaptivity, and which is often undervalued for the economic and environmental effects on the building life. In this regard, the different process stages in which the LCA of an adaptive facade has the most impact (Q.30) show how perfectly apodictic it is for the interviewees (90% of the respondents) to carry out an LCA during the phase design, and not ex-post, as unfortunately often happens (i.e., during a sustainability certification phase). To the question about the type of input data for the design of adaptive facades (Q. 32), 87.50% of respondents use product specifications and the BIM environment is used by 50% of respondents (20/29) (Q.33).

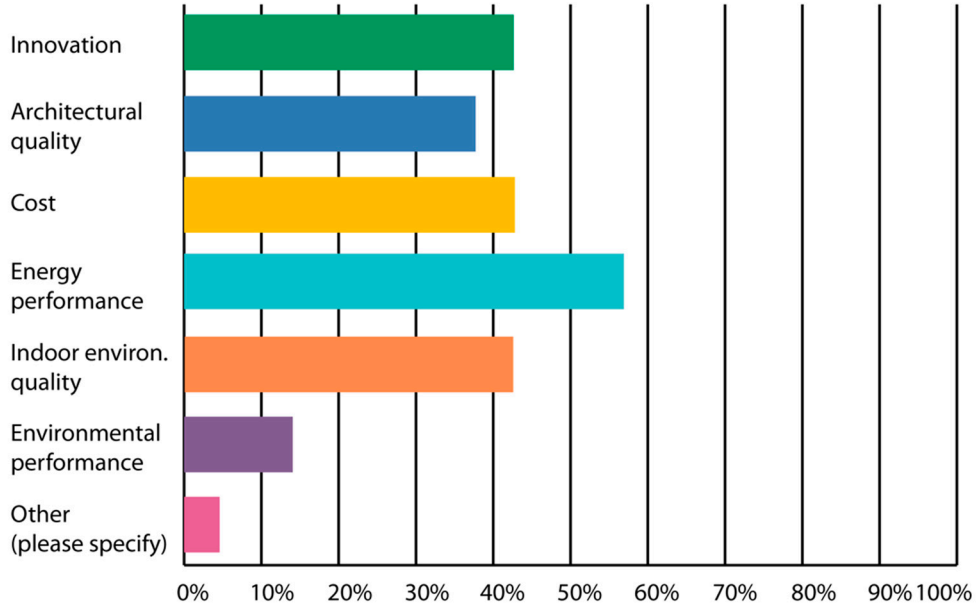


Figure 12. Q.29. Which factor(s) influence(s) the design and manufacturing of adaptive facades? (multiple-choice option).

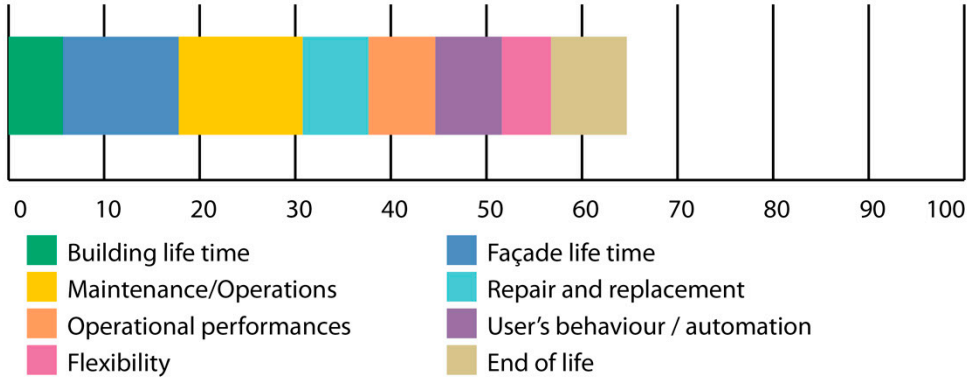


Figure 13. Q.31. Which of the following scenarios would be relevant within an adaptive facade LCA? (multiple-choice option).

3.5. Evaluation of the Usability of the LCA Design Tool

About 62% of respondents answered questions related to the user-friendliness of the proposed mapping. When asked about environmental impacts on the single life cycle phases (Q.34), the most relevant was the supply of raw and secondary materials (44%), followed by the use phase (34%) (Figure 14). For all the respondents, among the proposed design goals that support an LCA of an adaptive facade (Q.37) does not emerge a determining factor (Figure 15).

All of the above parameters represented in the mapping (Q.38), qualitative parameters, as well as those related to the operational and end of life phase, are preferred among stakeholders.

About the most decisive aspect for the use of mapping (Q.35), the interviewed focused on innovation (22%) and energy performance (22%). Overall, 94% believe that the mapping is very or on average useful, in particular, to highlight problem areas (67%), during early design phase (Q.36). This confirms how this tool is aimed at making designers understand and reflect on the complexity of the facade systems from many points of view.

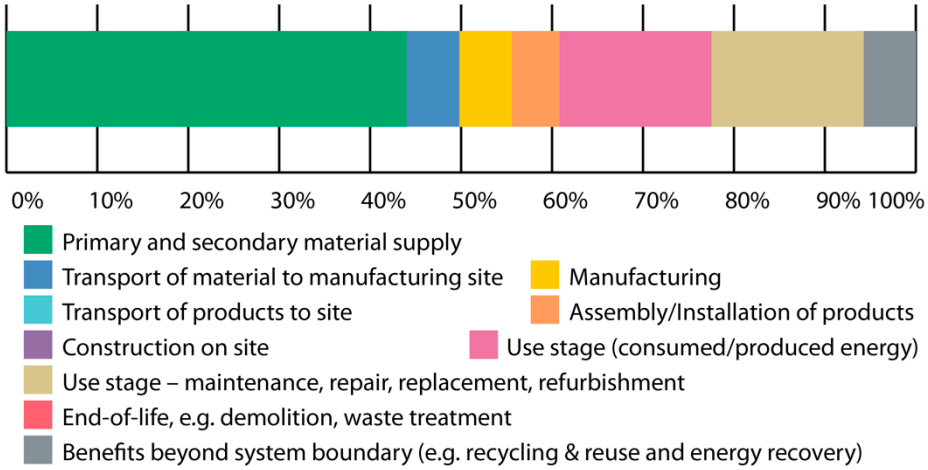


Figure 14. Q.34. In the event that you carry out an LCA on an adaptive facade, which life cycle phase do you assume will have the highest environmental impact?

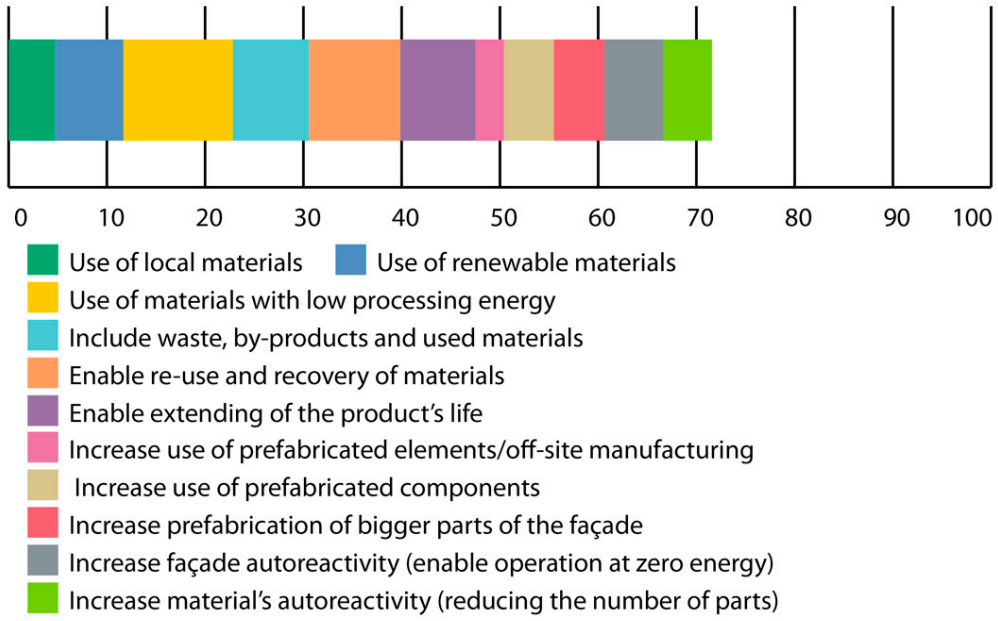


Figure 15. Q.37. In the event that you carry out an LCA on an adaptive facade, what would be the design scope?

4. Discussion

Results can be resumed in the following three groups of points:

- the feedback obtained is positively considered given the limited scope of the issues addressed. A cross-analysis on Part 1 and Part 2 shows that respondents are mainly designers/consultants whose degree of direct experience on LCA-type tools and sustainable building protocols is not related to designing adaptive facades. Despite that, the concern in the proposed subject of the survey (LCA and adaptive facades) has been common for the 73% of the interviewed;
- one of the main existing barriers to the application of LCA in the design phases is represented by the lack of awareness on environmental issues due to an absence of sustainable and long-term market models. This is the reason why Property managers and investors did not respond to the survey;
- one of the main gaps to the application of LCA is the lack of input data, especially regarding the use phase of adaptive fa cades (multiple-choice answer: 58% of interviewed).

With specific reference to them:

- the analysis of the words used in the proposed classification system highlights that Autoreactive Building Skins are the most investigated and/or produced technology;
- beside energy efficiency and indoor environmental quality, designers are concerned by other life cycle performances such as maintenance/repair efficiency and recycling/reuse potential at the end of life phase (multiple-choice answer: both 53% of interviewed);
- despite that, among the proposed design goals that support an LCA of an adaptive facade does not emerge a determining factor;
- innovation is a priority as adaptivity is still a developing technology;

With regard to the usefulness and usability of the proposed mapping:

- the interest is distributed among the various activities of the stakeholders and increases for those involved in research and sustainability.
- the usefulness and usability of the mapping are verified, especially considering that the BIM environment is the basis of computerized optimization methods (one-choice answer: 83% of interviewed).
- the mapping is very or "on average" useful, in particular, to highlight problem areas during the early design phase (one choice answer: 94% of interviewed).

Those outcomes suggest that to undertake a work of acknowledgement of LCA methodologies in the Italian building sector requires future involvement of real estate investors throughout dissemination of cost/benefit analysis and sustainable and long-term market models capable of guaranteeing a return on short-term investments.

Sustainable building protocols such as LEED may be the instruments to carry on this purpose because of their growing acceptance among designers and investors which both have responsibilities in the early design. Then, new pilot credits focused on innovative design methods and adaptive facade technologies should be proposed by research committees aiming at creating common metrics for sustainable performances.

On the other side, adaptive facades represent a challenging field of research, autoreactive technologies being the main trend by the whole of biomimetic building skins, designed focusing to reducing the use of energy inputs and consequently environmental impacts. Having in common the same parametric design method, the proposed mapping is likely to be used by these designers for identifying problem/solution areas in a life cycle approach. As underlined by cited studies, the involvement of multidisciplinary knowledge can boost the development of these design tools.

5. Conclusions

Architectural design is a highly complex task as performance requirements are growing with the challenge of sustainability goals. Solutions can be found through a multidisciplinary and biomimetic approach as long as new design models and tools evolve.

Although Life Cycle Assessment and the BIM environment in building design is very far from being a common practice, because of existing gaps and barriers, parametric mapping of design variables play a more user-friendly role in architectural sustainable technology design.

Italy's green construction market is estimated to grow driven by government's plans to upgrade building infrastructures, through incentives and regulations. At the same time, building product manufacturing is a core sector of economy in Italy. In this scenario, a profitable outcome would be focusing further research on applying the parametric mapping on a case study of an adaptive building product to achieve environmental scopes and introduce competitive factors and boost innovation on the Italian industry.

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