



Review

How Lack of Knowledge and Tools Hinders the Eco-Design of Buildings—A Systematic Review

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Abstract: The building sector is responsible for extensive resource consumption and waste generation, resulting in high pressure on the environment. A way to potentially mitigate this is by including environmental considerations during building design through the concept known as eco-design. Despite the multiple available approaches of eco-design, the latter is not easily achieved in the building sector. The objective of this paper is to identify and discuss what barriers are currently hindering the implementation of eco-design in the building sector and by which measures building designers can include environmental considerations in their design process. Through a systematic literature review, several barriers to implementation were identified, the main ones being lack of suitable legislation, lack of knowledge amongst building designers, and lack of suitable tools for designers to use. Furthermore, two specific tools were identified that allow the inclusion of environmental consideration in building design, along with nine design strategies providing qualitative guidance on how to potentially minimize energy and material consumption, as well as waste generation. This paper contributes a holistic overview of the major barriers to and existing tools and method for the eco-design of buildings, and provides guidance for both future research and practice.

Keywords: eco-design; sustainable design; circular economy; life cycle assessment; climate change mitigation; construction industry



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1. Introduction

Construction activities are responsible for extensive materials and energy consumption, consequently making them responsible for the related impacts on the environment and human health. Over the last century, the consumption of building materials has increased with a growth factor of 34 [1]. Furthermore, in 2017 buildings were found to be responsible for 39% of global energy-related greenhouse gas emissions [2]. If we are to achieve the 1.5 °C target of the Paris agreement, the emission curve needs to be broken. The building design phase can shape this development, as a large percentage of a building project's outcome is determined during the design phase [3]. This means that to affect the outcome of a design process, one needs to be involved as early in the design process as possible, where the degrees of freedom are highest.

A concept offering the integration of environmental concerns in the design phase of a product is eco-design. This concept originally developed in the 1970s through recognition of the emerging environmental crisis [4]. Nowadays, the ISO standard focusing on eco-design of consumer products ISO14006:2020 defines eco-design as “a systematic approach, which considers environmental aspects in design and development with the aim to reduce adverse environmental impacts throughout the life cycle of a product.” [5]. Thereby, eco-design can be defined as

a systematic way of dealing with environmental concerns in the product design and development process [6]. Within eco-design, the two core activities are environmental assessment and environmental improvement, i.e., reducing the adverse environmental impact of a given product or system [7]. Ever since the concept of eco-design emerged, research has focused on the development of eco-design tools and methods [6,8]. Within the past two decades, several literature reviews and research projects compiling knowledge on eco-design have been carried out. Some of the reviews focus on classifying the existing tools [9–12], while others are more focused on future trends of the tools [8,13]. However, literature is primarily concerned with eco-design in relation to product design and development. Rousseaux et al. (2017) developed a guide for companies to help choose the correct eco-design tool, based on a literature review of existing tools [12]. In total, 629 tools, some of which are relevant for the building and construction sector, were identified and categorized. Rousseaux et al. (2017) focus on categorizing the tools, without describing in detail the features of these tools or considering their usefulness for designers.

Even though various tools and methods exist, implementation of these in the building sector is lacking [14,15]. The few existing studies in the building/eco-design nexus address different facets of this issue, i.e., they focus on one geographical location, or focus on a single eco-design tool [16–18], which means that these studies also offer contradicting results. The validity of these studies, and their results, are thereby limited due to their scope of analysis. Therefore, all studies connecting buildings and eco-design need to be gathered to have more generally valid conclusion. Furthermore, eco-design was developed to fit the scope of product design [4], however, building design differs from the design of products in scale, temporal scope and complexity [19]. Where a product should fulfill one function a building is the sum of many products each fulfilling their part of the entire building's functionality. A product is manufactured, so are the parts and materials of a building, but the building itself is constructed on site. Furthermore, when a conventional product reaches the consumer, it is used for a certain, often short, period and then disposed of. A building can stand for centuries and have several owners and functions. Summing up, the differences between a product and a building resonate in the way they are designed, ergo the way to eco-design a building must differ from the way one eco-designs a product. Following this argument our hypothesis is that the tools and methods for eco-designing a building are not the same as for products, and the barriers to implementing eco-design in the building sector are not the same as for the manufacturing industry. Therefore, eco-design of buildings and the barriers for its implementation in the building sector needs to be studied separately from the eco-design of other products. As described in the previous paragraph, application of eco-design on buildings is scarce in the contemporary literature and an overview of the challenges in this context is missing. Furthermore, the lack of implementation suggests that the environmental impact mitigation potential of eco-design is currently unexploited in the building sector.

The objective of this paper is, therefore, to identify how environmental considerations can be included in the building design process and the barriers to implementing this in the building sector. Thereby identifying gaps in research and potential for future work by answering the following research questions.

1. What are the barriers to implement eco-design of buildings in the building sector?
2. Which tools and methods exist for eco-designing buildings?

Thus, this study will focus on identifying and explaining the current state of eco-design of buildings in the building sector, thereby identifying gaps and possibilities for future research.

2. Method

To answer the research questions and fulfil the objective of this paper, we chose to conduct a systematic literature review. That is because this method provided a structured way of gathering and synthesizing all the relevant scholarly information to answer the research questions. For instance, in comparison to a critical review which is focused on crit-

ically assessing a given research topic based on current published knowledge, a systematic literature review requires an explicit protocol, i.e., a set of keywords (search string) to search for and a clear way to filter out irrelevant papers through predefined exclusion criteria [20]. The systematic literature review presented here included publications from 2009 to 2020 (October), both years and month included. Only articles from peer-review journals were included, thereby excluding all gray literature (book chapters, conference papers, magazine articles, etc.). For the search we used Google Scholar. Preliminary tests showed that this returned the same search results as Scopus and Web of science, plus the latest literature, and was therefore considered the most effective search engine. The systematic literature review was carried out through three searches in the order indicated in Figure 1. The first search resulted in an insufficient number of papers, seven in total, potentially relevant for answering the research questions. Therefore, a second search was conducted to find more general publications on eco-design. The second search resulted in 13 papers claiming to be about eco-design in general, but after screening it was evident that these publications were focused on product design. Hence, there was still insufficient information to answer the research questions. Thus, we used the 20 articles retrieved from the two searches to create a list of alternative keywords to use instead of eco-design/ecodesign. The final list is shown in Figure 1 under search 3, while it is outlined in supplementary material how we arrived at this list. The publications obtained in search 2 were only used to create the list of keywords for search 3, while the publications in search 1 were added to the final sample of papers together with those obtained in search 3. In total, 113 papers were reviewed.

As seen from Figure 1 each search initially provided more publications than was included in the final sample of papers. To decide whether a publication should be included or not we conducted a screening process as outlined in Figure 2. When we had obtained the final sample of papers, they were classified according to the year of publication, country affiliation of the first author, journal of publication, and which research question it was relevant for answering. This was used as a base for the results generated and can be seen in the supplementary material. We used the year of publication and geographical affiliation of first authors to analyze the temporal and geographical distribution of the reviewed papers, respectively, see Section 3. When conducting the review, we found that scholars related the identified barriers to implementation of eco-design, to different groups both outside and within the building sector. In order to ease presentation, we chose to explain the barriers in relation to these so-called stakeholder groups, see the results in Section 4. The division of the barriers into the four groups was undertaken based on a qualitative evaluation of which groups the identified barriers from each publication belonged to. Furthermore, we noticed during the review that the identified eco-design methods had different features, some quantitative and other qualitative. It was chosen to present the methods according to this. Therefore, what we here refer to as tools are eco-design methods with quantitative features, see Section 5.1, while what we here call strategies are eco-design methods with qualitative features, see Section 5.2.

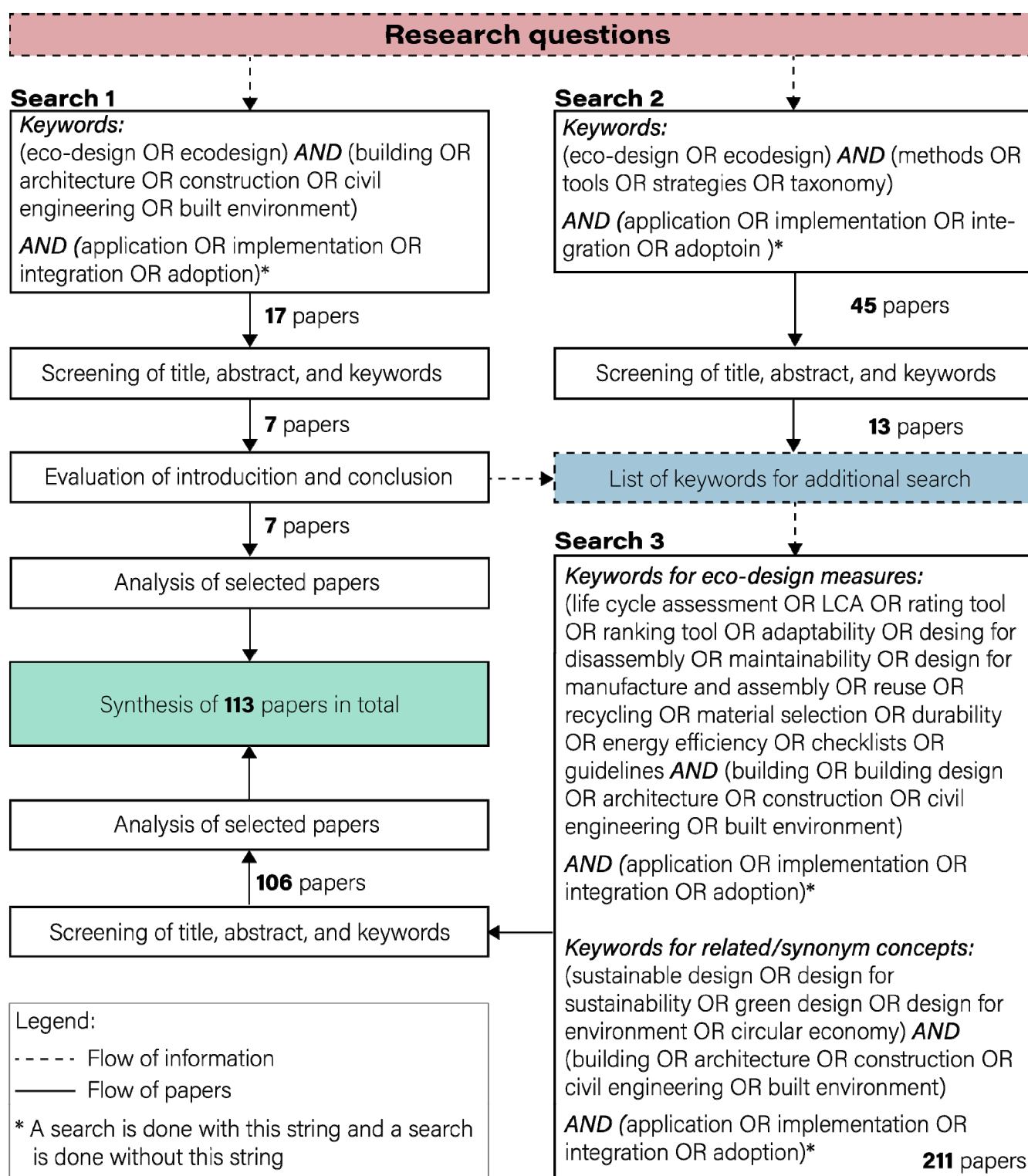


Figure 1. Schematic of the method used for conducting the systematic literature review.

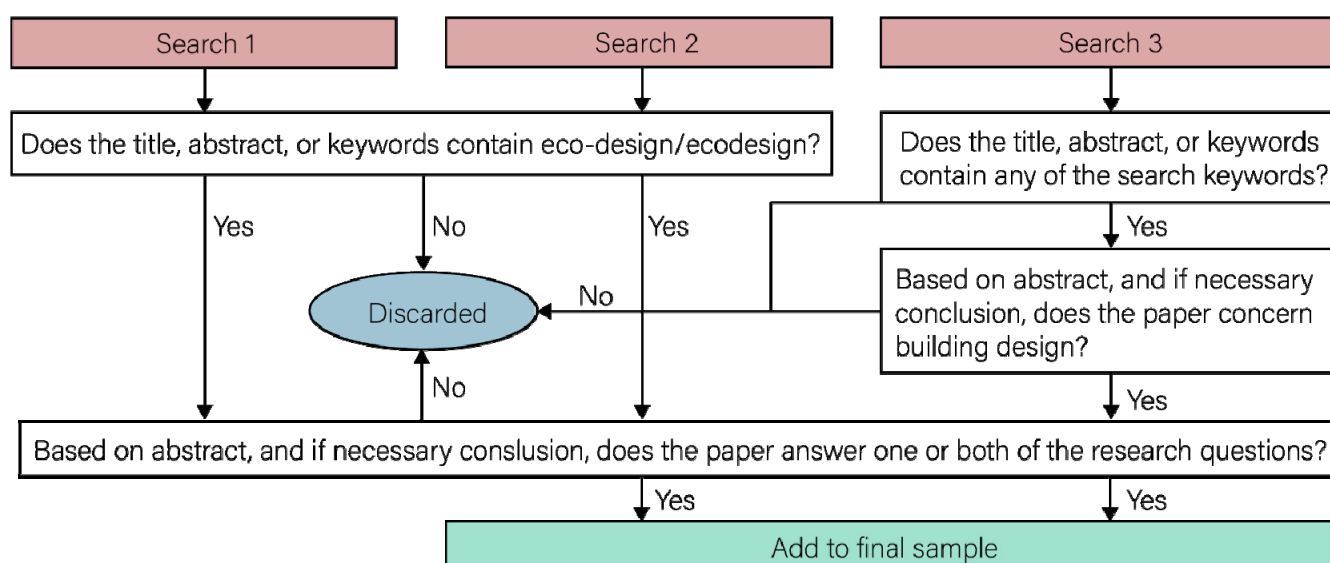


Figure 2. The screening process used to filter irrelevant literature.

3. Analysis of Publications

Figure 3 shows the geographical distribution of the reviewed papers, and the background data can be seen in supplementary material. The literature is concentrated in European countries, as 60 out of the 113 publications are from a European country. The remaining publications are predominantly distributed between North America, China and Oceania, with 34 publications in total. From Figure 4 it can be seen that the number of publications on eco-design of buildings increased from 2009 to 2020. The number of publications does not increase steadily but varies over the years. For example, the number of publications decreases to nearly half from 2018 to 2019, only to triple from 2019 to 2020. The reviewed papers are published in a wide variety of international journals and the top three, with 19, 13, and 11 included papers respectively, are the Journal of Cleaner Production, Building and Environmental, and Renewable and Sustainable Energy Reviews. The full list of journals and number of publications reviewed from each journal can be found in the supplementary material.

4. Barriers to Implementation

Table 1 shows all the identified barriers divided into the stakeholder group for which they are relevant. Furthermore, the geographical and contextual scope of each identified barrier is outlined; see supplementary material for further information. The stakeholder group clients refer to all institutions, corporations and private people (such as real estate developers) investing in and financing building projects. The stakeholder group designers represents everybody that is directly involved in one or more stages of the design process, architects, civil and architectural engineers, experts, etc. The building sector stakeholder group refers to the part of the building sector involved with the material supply chain, such as building material and component manufactures. It is evident from Table 1 that the most relevant barriers, those mentioned by most scholars, are the lack of suitable legislations, lack of suitable tools/methods and lack of knowledge amongst designers, as well as lack of financial resources in the building industry.

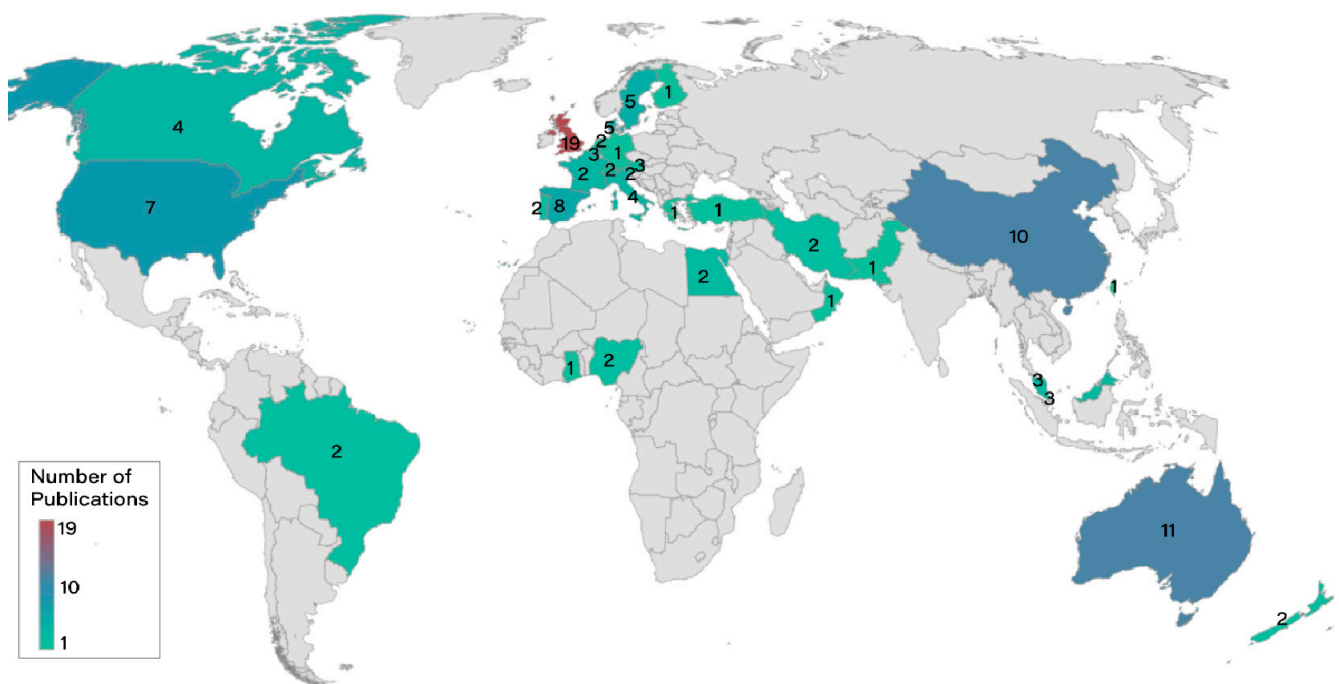


Figure 3. Geographical distribution of reviewed papers.



Figure 4. Temporal distribution of review papers.

Table 1. Barriers to implementing eco-design in the building sector based on reviewed literature divided into their respective stakeholder group.

Barrier	Geographical Scope	Contextual Scope	Publication
Clients			
Lack of awareness	Ghana, Nigeria, Developing Countries, United Kingdom	Adoption of green building practice and certification. Use of alternative materials, circular economy and construction waste minimization.	[21–25]
Lack of demand	Nigeria, Italy, Ghana	Eco-design for building designers. Adoption of green certification and use of sustainable materials.	[18,21,26]
Government/Policy-Makers			
Lack of suitable legislation	Italy, Ghana, Developing Countries, North-West Europe, Nigeria, United Kingdom, Taiwan	Eco-design for building designers. Adoption of green building practice and certification. Develop more adaptable building. Integrate circular economy and construction waste minimization.	[18,21–24,27–29]
Lack of support for eco-design	Ghana, Italy, Developing Countries	Eco-design for building designers. Adoption of green certification and circular economy.	[18,21,24]
Designers			
Lack of suitable tools and methods	North-West Europe, Nigeria, Italy, France, Europe, United Kingdom	Eco-design and eco-design tools for building designers. Adoption of green building practices, circular economy, and life-cycle performance assessment. Use of sustainable and alternative materials	[16,18,25–27,30]
Lack of knowledge	North-West Europe, Malaysia, Ghana, Nigeria, Malaysia, United Kingdom, Slovenia,	Adoption of green building practice and certification. Use of sustainable and alternative materials. Eco-design in small and medium-sized enterprises (SMEs). Developing more adaptable buildings. Integrating circular economy and maintainability.	[17,21,22,24,25,27,28,31,32]
Lack of professional skills	Nigeria, Slovenia	Use of sustainable materials. Construction waste minimization. Eco-design in SME's.	[17,23,26]
Lack of cooperation	Italy, Nigeria, Europe	Eco-design for building designers. Integrating construction waste minimization and life-cycle performance assessment.	[18,23,31]
The Building Sector			
Lack of financial resources	Italy, Developing countries, Nigeria, North-West Europe, Malaysia, Slovenia, Europe, United Kingdom,	Eco-design for building designers and in SMEs. Use of sustainable and alternative materials. Integrating green building practices, circular economy, maintainability, life-cycle performance assessment, and construction waste minimization. Developing more adaptable buildings.	[17,18,22,24,25,27,30,32]
Lack of knowledge	Developing Countries, North-West Europe, Nigeria, United Kingdom	Adoption of green building practices and circular economy.	[22,24,27,28]
Lack of professional skills	Developing Countries, North-West Europe, Nigeria	Adoption of green building practices and circular economy.	[22,24,27]
Lack of material availability	North-West Europe, Nigeria, United Kingdom, Malaysia	Adoption of green building practices, circular economy, and maintainability.	[22,27,28,31]

4.1. Barriers Related to Clients

Multiple scholars report lack of client awareness and, in turn, lack of demand as barriers to the implementation of eco-design in the building sector [22–25]. Agyekum et al. (2019) argue that when the clients are unaware of the possibilities for eco-designing buildings, or the potential benefits from this, it is difficult for them to show an interest in the subject and thereby also create a market demand [21]. In contrast, some scholars argue that it is a question of perception from the designers, as they perceive clients as uninterested and thereby not convinced that there is a real demand for eco-design [18,26].

4.2. Barriers Related to Government/Policy-Makers

Several scholars identify lack of suitable policies, codes and legislation as one of the main barriers to implementing eco-design in the building sector [18,21,24,27,28], some of which even state that adopting environmental strategies is in conflict with the current regulations [22,29]. Furthermore, existing environmental laws do not necessarily include what is needed for effective implementation [27]. For instance, the environmental regulations in Nigeria do not address construction waste [23]. Furthermore, the focus of the regulations is important. Kanters (2020) argues that because of a focus on operational energy performance in existing codes and regulations it is difficult to fit, for example, reuse of materials into them [27]. In addition, support and commitment from the government, policy-makers, and other public institutions, is important to further the implementation of eco-design of buildings. The fact that support is lacking is thereby a barrier [18,21,24].

4.3. Barriers Related to Building Designers

Currently there is a lack of suitable methods and tools to help building designers take the most environmentally enlightened and beneficial decision, [19,22,26,27]. A possible explanation of this trend is provided by [16]: the tools available are unsuitable because they are deemed unaligned with the designers' needs by those who have tried them, resonating to the rest of the industry and the tools are now perceived as not being useful [16]. Furthermore, some tools (e.g., life-cycle assessment) carry a high cost, e.g., from the needed software and required expert knowledge that might follow [30]. Before arriving at the stage where the tools and methods are needed, the designer first needs to know how to eco-design a building, i.e., what to focus on during design. This knowledge can, for example, be gained from quantitative evidence of the benefits of implementing eco-design [17,28,32]. However, the knowledge is lacking and is thereby acting as a barrier to eco-design implementation [17,21,22,25–28,31,32]. Further barriers to eco-design implementation are lack of professional skills [17,23,26] and lack of cooperation within the design team [18,23,30]. Jusselme et al. (2020) argue that collaboration is lacking at the conceptual design stage, as architects are reluctant to involve engineers at this early stage of the design [30].

4.4. Barriers Related to the Building Sector

Scholars argue that the financial resources, or the willingness to use finances, to cover the (perceived) extra initial cost of so-called green buildings is lacking, and is one of the greatest barriers to eco-design implementation [17,18,22,24–27,30,32]. There are various reasons for this extra cost; some believe that sustainable materials and components have a higher cost [18,22,24,27]. A change in design procedures, as introduced by eco-design, will lead to an extended design process requiring extra time, and thereby extra finances from the extension of the project schedule [22,26,31]. Furthermore, certain eco-design tools are costly to use and/or require expert knowledge, which again requires financial investment [17,30]. The increased cost can be a problem in particular for companies with limited funds, such as small- and medium-sized enterprises [17]. Beyond the financial barrier, scholars argue that the lack of knowledge and lack of professional skills barriers, as outlined in Section 4.3, are also relevant for members of the supply chain [22,24,27,28]. Furthermore, scholars argue that the lack of knowledge and professional skill within the building sector in combination with the fragmented nature of the supply chain can lead to the final barrier, and lack of

material availability [22,27,28,31]; i.e., less impacting materials, such as reused materials, are difficult for the suppliers to provide.

4.5. Means to Overcome the Barriers

The identified barriers are shown in Figure 5 together with the means scholars propose to overcome them. The barriers relating to clients and to government/policy-makers are marked as external barriers, i.e., barriers related to stakeholders not working directly with building design or construction. Thereby the two remaining barrier groups are internal barriers. The means to overcome the barriers related to clients is providing information to the clients and the general public, thereby, creating much-needed awareness, through the media, seminars, workshops, etc. [22,24]. The stakeholders responsible for creating awareness could be both government/policy-makers and the designers. The means to overcome lack of suitable legislation is to formulate new legislation and codes, of which the government/policy-makers are responsible [24]. Other than fixing the barrier regulatory evolution might trigger designers to include environmental considerations, due to the proactive nature of construction professionals, with a tendency to maintain current practices [16,21,22]. Furthermore, scholars argue that regulations including requirements for using eco-design tools and methods could push forward the use of existing ones [16,30]. The government can provide support by being a front runner, e.g., by environmentally upgrading/certifying public buildings [21,24] thereby using their positions as building owners and developers to push forward the construction market [18]. Another form of governmental support is fiscal incentives such as tax relief/relaxation [18,21,24]. As shown in Figure 5, fiscal incentives could be a means to overcome the lack of financial resources [24]. Developing more suitable eco-design tools and methods, e.g., checklists for the designers to follow, could help overcome this barrier [27], even though it is not just a question of suitability but of the designers being familiar with existing tools and methods as well [16]. Finally, providing training for construction professionals is seen as a solution to generate better knowledge on eco-design and simultaneously improving their skills [17,21,22,28,32].

5. Existing Tools and Strategies

5.1. Tools For Eco-Design of Buildings

In the reviewed literature, two tools relevant for the eco-design of buildings are identified: life-cycle assessment (LCA) and green building certification schemes. The definition, use, limitations of these tools as well as their potential developments to overcome the limitations are outlined below.

5.1.1. Life-Cycle Assessment in the Building Design Process

LCA is a standardized method (ISO standards 14040 and 14044) for assessing environmental impact potential from a product or service during its entire lifecycle. LCA is relevant for eco-design through its ability to assess and quantify environmental impacts for the entire lifetime of the building [33–38]. Through LCA, the designer can identify main impact contributors and the impact's sensitivity to design changes, thereby providing the designer with knowledge on the most important areas to focus an eco-design effort. To gain this knowledge, information about the material composition and quantities as well as projections of resource consumption during use is needed. Unfortunately obtaining this data can often prove to be too laborious and time consuming a task for the designer [39,40]. Furthermore, for the designer to be able to easily make changes to the design the LCA needs to be integrated as early in the design process as possible, however, at this stage the data required are mostly unknown, because the design is not finalized yet [33,38]. The availability of the data increases as the design process moves along. However the design freedom decreases at the same time, so it becomes harder and more costly for the designer to make changes. This phenomenon is known as the eco-design paradox [39] and it means that LCA is more appropriate for later stages of design because the data required will often be available. Simultaneously, the designers need LCA in the early design stages. However,

Roberts et al. (2020) indicate that when LCA is introduced too late in the design process the assessment become reactive to the design. For the designers to be provided with environmental knowledge, which can trigger design alterations, the design should react to the assessment [39]. Beyond the limitation due to severe data requirements, LCA is also a complex tool to use and understand, and it might require expert knowledge to conduct an LCA [30]. Furthermore, the results will always have a certain level of uncertainty, e.g., due to lack of specific data [41–43]. Literature covers a large sample of completed building LCAs that could potentially aid designers in gaining environmental information without having to conduct an LCA themselves. Unfortunately, comparison between studies is very difficult. Firstly, this is because of varying scopes in the cases that are assessed, such as geographical location, climate, used data quality, study period, building lifespan, etc. [34,36,43]. Secondly, it is because variations in the way the LCA is conducted, e.g., in choice of software, system boundaries, included impact categories, and applied impact assessment method [41,44–47]. However, both Moncaster et al. (2019) and Röck et al. (2020) demonstrate that with the right method and enough cases it is possible to draw general conclusions [47–49].

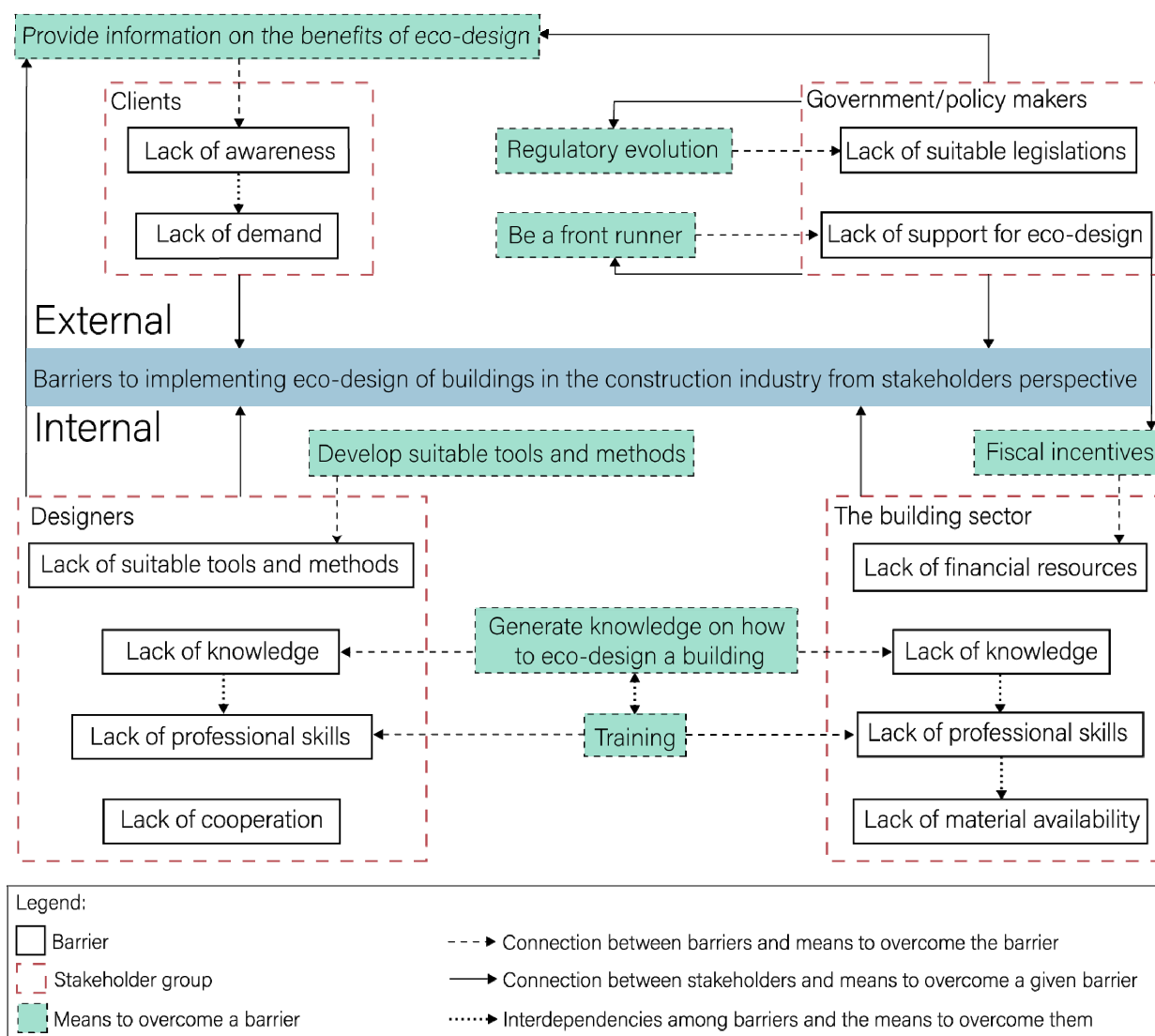


Figure 5. Barriers to implementing eco-design in the building sector connected to the potential means to overcome the barriers.

Scholars propose various approaches for making LCAs more suitable for designers: firstly, coupling LCA with building information modeling (BIM). When a BIM is created

the designer has access to all the material data needed and the LCA can be conducted from this [37,49] thereby eliminating the time-consuming data collection. However, if steps are not taken to adjust/lower the complexity of the BIM, it is just as unsuitable for early design as traditional LCA [39]. A way to make the BIM less complex, and thereby more suitable for early design, is constructing a database containing environmental data on relevant materials, subsequently conducting the BIM and consequently LCA from this database and, for example, when only having knowledge on the overall shape and material composition of the building [50–54]. Doing so can help the designers check the environmental performance of different design solutions against each other in a time-efficient manner. The simplifications, however, come at a cost for instance that the method/model is only suitable for early design because the database is at component level only [51,52] and limited to materials and components frequently used [54]. Another way to make LCA more suitable for designers is simplifying or streamlining the method itself. Beyond the simplification methods when coupling with BIM, optimizing data collection and use of databases, LCA can be simplified through reducing the scope of the study, e.g., included lifecycle stages or reducing the number of assessed environmental impact categories [41,55,56]. However, care should be taken when making these simplifications because the results might not be universally reliable [41,49]. Božiček et al. (2020) explores the use of environmental product declarations (EPDs) as a substitute for conducting an LCA and thereby making the process simpler, doing this is, however, still in the very early stages [57].

A third possibility for making LCA more suitable for early design stages is through parametric design. This makes it possible for the designer to guide early design stages by working with a variety of design alternatives and evaluate them against, in this case, environmental criteria in order to identify the optimal solution [39,40]. Even though this approach looks promising, it is still in its infancy [39]. Malmqvist et al. (2011) developed in consultation with stakeholders (e.g., clients and architect) a guide for the use of LCA in the building sector [37] recommending that designers start with a simplified version of LCA and then move on to more complex versions. The final aspect to facilitate the use and suitability of LCA in building design is the use of benchmarks and target values to help designers interpret the results by giving them something to which to relate their design solutions [39,58,59]. Environmental impacts induced by buildings can differ greatly depending on the region. Therefore, the development of region-specific benchmarks could be encouraged [46].

5.1.2. Green Building Certifications Schemes

Green building certifications schemes, also known in literature as green building rating tools, are based on a predetermined set of criteria and benchmarks, both qualitative and quantitative, used to score a building project's performance [60–62]. The results are weighted and accumulated into a single score, which determines whether the building can be certified and what level of certification it potentially can gain via specific design changes. Building certification is becoming increasingly popular and approximately 600 schemes exist around the world [61]. The best known and most used schemes are LEED and BREAM. For the building designers, these certification schemes can offer guidance to help meet a given criterion and provide benchmarks so the designer has something to compare the performance of a given design solution to [63–65]. Chen et al. (2015) demonstrates how a group of the most commonly used certifications schemes can be used to guide certain aspects of the design, in this case energy-efficient design [66]. However, the way the schemes are able to guide the design and how well they are able to do so varies from one scheme to another [65]. Furthermore, scholars argue that one of the biggest limitations to these schemes is the fact that they are not homogeneous. The schemes vary in terms of criteria included, what scientific content lies behind the criteria, and how these are weighted [60,62,67,68]. This hinders comparison amongst the schemes and increases the risk of arbitrarily choosing criteria to obtain the desired certification results. Scholars argue that energy performance, especially operational performance, has been weighted very

high compared to other criteria [67,69]. In addition, the leading certification schemes are programmed according to geographical and local climate conditions, which hinders their comparability, but is favorable in terms of guiding the designer [35]. Moreover, most of the certification schemes set out not just to certify environmentally but more holistically sustainability as a whole, i.e., also looking at economic, social impacts/dimensions. However, in this regard the schemes are inhomogeneous as well and include more environmental criteria [61,65,68,70,71]. Ismael presents a quantitative analysis method that can potentially aid practitioners in seeing through the varying scopes of the certification schemes [68]. Furthermore, Wen et al. argue that there is a general trend of the schemes moving more toward an equal focus on the three pillars of sustainability [70]. Generally, the certification schemes require the quantification of the building project's environmental impacts, e.g., by undertaking an LCA. However, Ismael (2018) argues that the schemes offer little to no guidance on how this assessment should be conducted, level of detail, what lifecycle stages should be included, etc. [72]. Furthermore, the schemes often measure performance based on average industry benchmarks (current building codes), and for the schemes to push for better building practices the performance goals need to be absolute [60]. Despite the limitations of the certification schemes, it can be argued that they have one clear advantage: ease of communication. The fact that all aspects considered in the certification scheme are accumulated into one single score makes it easy to communicate. Moreover, this could be of value for the client, e.g., in terms of branding, which could be a way of providing a clear incentive for eco-designing.

5.2. *Strategies for Eco-Design of Buildings*

Based on the reviewed literature, the qualitative measure designers can take for eco-designing a building can be summed up in nine strategies. Figure 6 shows all the identified strategies in relation to where in the building's lifecycle they are relevant. The strategies, Material Efficient Design, Design for Waste Minimization, and Design for Circular Economy are relevant for the entire lifecycle of a building. Energy Efficient Design could also be relevant for entire building lifecycle, however, due to the focus on the operational stage in the literature it was chosen to place this strategy here. Furthermore, Material Selection/Substitution is relevant in any situation during the buildings life where material resources are needed. In the following text, each of the identified strategies will be described.

5.2.1. Material Selection/Substitution

This strategy focus on guiding the designer to choose less environmentally impacting building materials or substitute traditionally used materials with less impacting ones [73–75]. The reduced impacts come from minimizing these during raw material extraction, material production and transport. For instance, by focusing on the use of natural, recycled, reused, and local materials, as well as alternative materials e.g., in the production of cement, during design. Furthermore, initiatives such as use of renewable energy during production and using the materials correctly/to their full potential could also result in lower impacts [73,74]. Material substitutions seem to have the ability to reduce embodied carbon [73], embodied energy [75] and greenhouse gas (GHG) emissions [74]. Two publications assessing the environmental benefits of material substitution/selection, based on LCA, were identified and conclude that using wood (if considered carbon neutral) and recycled/recovered materials can lower the embodied impacts [76,77]. However, the use of recycled/recovered materials and components are currently limited by an immature manufacturing processes and supply chain [74,76]. Furthermore, the employment of this strategy is hindered by initial investments and lack of skills/experience among professionals [74].

5.2.2. Design for Manufacture and Assembly

During building construction, waste will be generated, mainly from material cut-offs and from mistakes in either drawings or from workers on site [78]. Design for Manufacture and Assembly (DfMA) is focused on minimizing the generated waste, and material

consumption that follow, through increasing the buildability/constructability in the design phase [79–81]. The key to DfMA is reducing complexity, through standardization, minimizing the number of materials and components, as well as limiting/facilitating assembly and handling on site [79,81–83]. Furthermore, Gerth et al. (2013) argues that DfMA is about integrating previous experiences in new design projects, by creating a feedback loop between design and manufacturing/assembly functions [81]. The identified benefits are all of a qualitative nature, as there is a limited amount of empirical evidence of the effects of DMA in construction [80]. Thereby, it is believed that application of DfMA can reduce waste and defects during construction, shorten construction time through increased productivity which will result in lower cost and higher quality [80,82–84]. DfMA originates in the manufacturing industry and has a long history of use therein [82,83]. This strategy is still in its infancy because the features of the building sector are different from those of manufacturing industry and the adaptation of manufacturing industry is lacking [83,84]. Furthermore, the limited number of examples in literature gives the impression that DfMA serves prefabrication only [84]. That being said, scholars argue that to enhance the benefits of DfMA it should be applied together with the right degree of prefabrication, as well as using BIM for assessing the buildability of a given design solution [82,84,85]. Furthermore, scholars argue that the next step for Design for Manufacture and Assembly is the development of design guidelines, as the main source of explicit knowledge on this design practice [80,81,83].

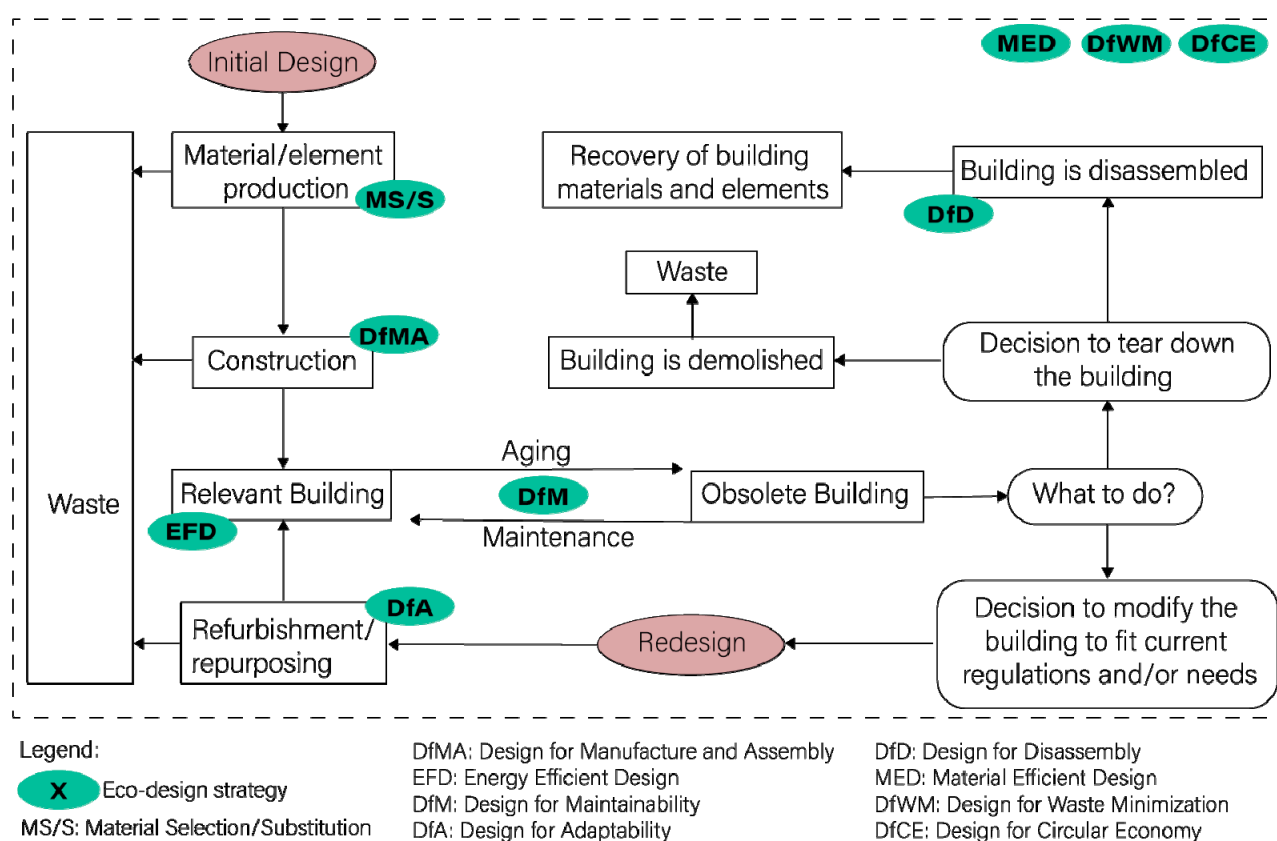


Figure 6. The design strategies relevant for eco-designing buildings based on the review literature. The strategies are placed by the building lifecycle stage they concern and can potentially affect the most.

5.2.3. Energy-Efficient Design

This strategy is focused on improving energy efficiency, and thereby reducing the energy consumption, throughout the lifecycle of the building [86,87]. This means reducing both operational energy and reducing embodied energy, i.e., the energy needed for material production and construction of the building. To increase the operational energy efficiency,

the designer can focus on optimizing the building geometry and orientation, natural lighting and ventilation, passive heating and cooling, and minimize the energy loss through the envelope by proper insulation [86–89]. Furthermore, the designer can include renewable energy sources e.g., solar, geothermal, and biomass [88]. To reduce embodied energy, the designer needs to focus on choice of materials and construction method, and considering the potential energy consumption during the end of life to reduce it [87]. Designing for energy efficiency can reduce the operational energy consumption of a building and the lifecycle carbon emissions [77,90]. However, the carbon savings are dependent on the energy mix. Furthermore, Capeza and Châfer (2020) found that there are a limited number of studies relating to how proper (energy-efficient) design decrease energy use and even less reporting on the potential reduction in environmental impacts [88]. Furthermore, this strategy is limited by the fact that ensuring energy efficiency during use does not necessarily ensure a reduction in energy consumption or environmental impacts throughout the lifecycle of the building, as the measures for decreasing operational energy might need an increase in embodied energy, and other embodied impacts [86,91,92]. To achieve the minimum lifecycle energy consumption there must be a balance between operational and embodied energy [92]. Georgiadou et al. (2012) argues that there is a need for an assessment method for the energy performance of buildings that integrate lifecycle thinking, to better anticipate and proactively manage future trends affecting the energy performance [93]. Zabalza et al. (2013) propose a methodology for this that is linked to LCA, based on stakeholder feedback and guiding the user through a simplified version of LCA to design for energy efficiency during the entire lifecycle of the building [94]. Peuportier et al. (2013) propose linking thermal simulations with LCA account for the energy consumption related to building inhabitants and the embodied energy at the same time [95].

5.2.4. Design for Maintainability

When a building is in use, maintenance will be needed at times to keep the building from becoming physically obsolete [96]. This strategy is focused on reducing the need for defect-induced maintenance, by including knowledge of the most frequently occurring building defects [97,98]. This strategy is about involving the facility manager, or facility management knowledge in the design phase. Important criteria in designing for maintainability is durability of building materials, easy access and performance of cleaning, repairs and replacement of materials and components [99]. Only one paper addresses the environmental benefits of applying this strategy showing that the use of durable materials show promise in terms of reducing embodied impacts. However, these savings are sensitive to service life [77]. Beyond the lack of environmental benefit documentation, scholars argue that there is a need for developing a checklist or guidelines providing the designers with practices to follow [98]. Asmone and Chew (2020) propose a method for assessing design solutions in terms of maintainability, predicting the probability of defects, as a way to facilitate Design for Maintainability [97].

5.2.5. Design for Adaptability

After a period of time, a building can become obsolete and regular maintenance is no longer enough to remedy the situation [96]. There are now two possibilities, modifying the building so it becomes relevant again, or tearing it down. Design for Adaptability focuses on making this modification easier by incorporating the capacity to change the building layout, encouraging the choice of modification instead of tearing down the building, and thereby aiming at longer life [89,96,100–104] with the additional aim of reducing material consumption and waste from building renovation and refurbishment. An adaptable building should be designed so there is room for the function and context (economic, social, legal and political) of the building to change and adjustments can be made with ease [96,102]. A building can be made adaptable through initiatives such as dividing building elements into layers so these can be adapted with minimal damage to the other layers, through designing a building without a specific use in mind, through using interchangeable components, and

though designing for disassembly (see Section 5.2.6) [103]. Furthermore, Heidrich et al. identified through a literature review 172 characteristics associated with making a building adaptable, see [102] for more information. Rasmussen et al. (2020) demonstrated through an LCA that designing for adaptability can reduce embodied carbon across the building lifecycle, but the results are sensitive to the service life of materials and the assumed disassembly solution [77]. Manewa et al. (2016) found that more than 60% of the buildings in their chosen urban cluster change the original use during life, thereby giving Design for Adaptability a significant potential for contributing achieving sustainability [100]. However, for the benefits of this strategy to be reached the initial design intents need to be fulfilled, which is both the responsibility of the designer by making it desirable and the owners as the decision ultimately come down to them [76]. This serves as a potential limitation to this strategy, as well as unknown cost and benefits from the implementation, and the need for a standardized assessment method to aid decision-making during design [102]. Various assessment methods exist, e.g., the method adaptSTAR based on the analysis of 12 adaptive reuse projects [101,105], or a causal loop diagram informed by a literature review [103]. Both lack real practice validation, which is needed for these methods to move on from their embryonic stage [96].

5.2.6. Design for Disassembly

If instead of choosing to modify the building when it becomes obsolete, it is decided to tear it down, two new choices arise. Should the building be demolished or disassembled? If the choice falls on disassembly, recovery of building materials and elements for reuse is facilitated, thereby minimizing waste at the end of building life [106]. The key to Design for Disassembly, also known as Design for Deconstruction, is choosing the right materials and components and connections between them, e.g., by minimizing the number of different components and their connections, make connections accessible, avoid binders and secondary finishes, use reusable, recyclable and lightweight materials [107]. Another important aspect is layering components and building parts according to their expected lifespan [106,107]. In this review, four publications identified the savings potential in environmental impacts on designing concrete structures [108] and steel structures [109–111] for disassembly. All found that there is impact savings to be gained, however, it is highly dependent on the number of reuse cycles and the service life of components [108]. Furthermore, there can be an increase in initial environmental impacts, i.e., impact from material use and construction in the original, first use cycle, building [110]. Kanters et al. (2018) argue that there is a need for tools and guidelines to aid designers in their efforts [107]. A possible way to this is by use of BIM to assess deconstruction and disassembly possibilities during design, as proposed by [112,113]. Tingley and Davidson (2012) propose a special LCA methodology to account for the potential environmental benefits of Design for Disassembly and thereby help the designer explore this during design [114]. Moreover, there is a need to gain knowledge on the deconstruction potential of different materials, as this can be key for the designers [107].

5.2.7. Material Efficient Design

The way a building is designed, layout, use of space, etc. affects the material consumption; therefore this strategy focuses on creating buildings with the intention of consuming less material resources throughout the lifecycle of the building [25,91]. This can be obtained through more intensive use of space (i.e., reducing per capita floor area), extending the lifetime by designing for adaptability, using materials with less adverse environmental impact, and designing for reuse and recycling of components and materials. Thus, this strategy has its own features and incorporates Materials Selection/Substitution, Design for Adaptability, and Design for Disassembly. Applying this design strategy has great potential for reducing Green House Gas emissions [91]. However, which part of the strategy to focus on depends on the regional specification, e.g., measures related to lifetime extension, reuse and recycling is of high importance in places with a large existing building stock. Furthermore, some

aspects of the strategy might induce higher savings in embodied impacts than others, e.g., reducing floor area per capita being more effective than material selection [76].

5.2.8. Design for Waste Minimization

During the entire life of a building, waste will be generated, e.g., during construction from material wastage from cut-offs and last-minute design changes, and during the end of life from demolition waste [78]. This strategy is focused on reducing waste at all stages of the building's life. To reduce waste during construction, the designer can design for prefabrication, use modular design, use standard size material/components, and design for improved buildability [22,78,115,116]. To reduce waste during use, the designer can design for adaptability [22,116]. While to reduce waste at the end of life, the designer can focus on designing for reuse and recycling of materials and components [87,116]. Therefore, this strategy has its own features and incorporates features from Design for Manufacture and Assembly, Design for Adaptability, and Design for Disassembly. Ajayi et al. (2017) argues that using tools like BIM could be beneficial for simulation/estimating the waste generation from design solutions, and thereby inform the designer about the best solution [116]. Such a tool is proposed by Llatas and Osmani (2016) although only focusing on construction waste [78].

5.2.9. Design for Circular Economy

The circular economy is concerned with eliminating waste as a concept, by turning it into a resource, and at the same time maximizing the value of materials [28,117]. Designing for a circular economy is about reducing, reusing and recycling, in that prioritized order, waste from a building and better managing material resources [118,119]. Design initiatives for a circular economy can be designing for modularity and off-site construction (use of prefabricated elements), Design for Adaptability, design for durability, Design for Disassembly, design for material recycling, Material Selection/Substitution, optimize shape and dimensions for reduced material consumption, minimize the number of different materials and components used, design components in layers dependent on their anticipated lifetime [28,118–120]. Consequently, aspects of all the other strategies, except energy-efficient design, are considered in the Design for Circular Economy approach. Furthermore, scholars argue that it is necessary to integrate professionals from the supply chain early in the design process to make plans and guidelines for ensuring the quality of the building material and components at the end of life [121,122]. Hossain et al. argues that there is a lack of cases. Therefore, the real-life consequences, environmental and otherwise, of designing for a circular economy are unknown [121]. The studies reviewed show mixed results when it comes to environmental benefits. In some cases it was possible to reduce emissions such as greenhouse gases (GHGs), however in some cases where the circular economy solution involved energy or material requiring an increase in emissions could be observed [123,124]. Furthermore, designing for recycling might not be beneficial if the recycling process itself is too resource demanding [123,125]. Furthermore, due to a lack of knowledge on environmental effects of implementing a certain circular economy design initiative the choice is most often based on intuition [120]. Another key challenge to this strategy is a lack of tools, guides and standard practices that could help designers over the uncertainties and difficulties with considering the buildings end of life during design [118,119,121]. Moreover, scholars argue that the supply-chain is not developed sufficiently in a circular direction to support this design strategy [119,121,126]. To aid the designer in determining the best design solution regarding the end of life performance, scholars propose different methods for evaluating this. Cottafava and Ritzen (2020) propose a method for evaluating the recovery potential of materials and components e.g., based on types of connection and their accessibility [127]. Akanbi et al. (2018) propose a BIM integrated model for evaluating the potential salvageability of materials and components based on a literature review on the subject [128]. Finally, Saghaei and Teshnizi (2011) propose a method for evaluating the recyclability of building materials [129].

6. Discussion

Previous literature reviews providing a holistic overview of the barriers to and existing tools and methods for eco-design have not focused on building design or the construction industry but on product design and the manufacturing industry. This paper sets out with the argument that these two industries are different and eco-design must, therefore, also include different aspects for buildings than for products. Some of the barriers to eco-design implementation in the manufacturing industry are the same as for the building sector: lack of suitable legislation, lack of client demand, lack of knowledge and professional skills amongst designers, and lack of financial resources or willingness to spend these on eco-design [14,15]. However, whereas building designers are lacking suitable tools and methods for eco-design, product designers have an abundance of tools to choose from and are having problems identifying which to use. Dekoninck et al. (2016) argues that this might stem from the focus on tool development in this field [15]. Rossi et al. (2016) conducted a literature review to identify the eco-design tools and strategies relevant for product design [14]. The tools that are the same identified for building design are LCA, fully and in simpler versions, and LCA integrated in computer-aided design CAD (the product designer's BIM), and similar strategies identified are Design for Disassembly and Energy Efficiency. Beyond this, Rossi et al. (2016) identified diagram tools (a simple, often matrix based, semi-quantitative way of evaluating environmental impacts), and checklist and guideline/guiding tools, which was not identified in this review [14]. In turn, this review identified the green building certification schemes as a tool, which possesses similar qualities as the checklist and guideline tools. Furthermore, Rossi et al. (2016) identified the design strategies of remanufacturing, which we excluded here as not relevant for the building sector, and the design strategy of materials recycling [14]. In fact, when conducting the search preliminary results pointed towards recycling as an important strategy. However, after a more detailed review results show that recycling cannot be classified as an individual strategy. Having identified other barriers to eco-design implementation and other relevant tools and strategies (for manufacturing industry) confirms our initial hypothesis that the building sector needs to be considered separate from the manufacturing industry. From the results we observed that while there is a focus on ensuring minimal operational energy consumption amongst the green building certification schemes, the strategies are more focused on reducing material consumption and waste generation, and the adverse environmental impacts that follow. Only one of the identified strategies deals with energy efficiency. It is important not to focus solely on operational energy as there can be rebound effects in terms of higher embodied impacts from energy-saving initiatives [86,91,92]. However, neglecting operational energy reductions would not be a sufficient solution either as this phase account for a high percentage of a building's lifecycle impact [34]. In turn, none of the strategies take a holistic view of reducing both operational energy as well as embodied impacts, from material consumption and waste generation. The certification schemes do this to a certain extent but still need further development not to be biased towards single scoring criteria. Consequently, the lack of holistic approaches for reducing both operational energy/impact and embodied impacts are identified as a gap in research which needs to be filled if we truly wish to mitigate adverse environmental impacts from buildings. Beyond this, the identified strategies focusing on reducing embodied impacts vary in terms of which lifecycle phases are considered and whether material consumption, waste generation or both are considered. Focusing solely on one aspect of reducing embodied impacts or one lifecycle stage could lead to rebound effects. Therefore, future research should take a holistic approach regarding the aspects within reducing embodied impacts and the lifecycle stages included, as well as reducing both operational and embodied impacts.

One of the main barriers for implementation is lack of knowledge amongst designers, and the remaining building industry. Designers are deemed responsible for providing the clients with the benefits of eco-design so these can generate a demand for eco-design, see Figure 5. However, it seems improbable that designers will be able to do so, while there is

a lack of knowledge among them. Thereby, to instigate the eco-design of buildings some entity needs to take responsibility for tool development and generation of knowledge. The lack of knowledge is a fact echoed in the current stage of the eco-design strategies. There is very limited knowledge on the environmental consequences of applying the strategies, and even though the strategies exist guidance on how to, for example, Design for Adaptability is lacking. The lack of knowledge amongst designers make them take decisions based on intuition or tacit knowledge, instead of making decisions based on evidence [27,120]. Furthermore, it can be seen from the identified barriers and the related means to overcome them that none of the stakeholders, internal as well as external, are identified as being responsible for providing this knowledge. How to provide this knowledge is thereby a gap in research. Through its possibility to quantify the environmental impact, LCA can play a great role in remedying the current situation. Researchers can use the full coverage of LCA to assess various eco-design solutions and thereby gather a pool of information on the environmental pros and cons of the design strategies. However, given the current issues with comparing LCA conducted by different scholars there is a need for transparency when conducting these studies. At the same time as gaining environmental knowledge, researchers can compile a pool of design examples that can be used to create guidance for making the strategies into actual design solutions. Another important barrier to the implementation of eco-design is the lack of suitable tools and methods. Each of the identified existing tools and strategies have the potential to contribute to the eco-design of buildings, insofar they are developed to overcome their limitations. The strategies need to be more holistic in their approach, as do the green building certification schemes. Furthermore, all but one [40] of the means proposed to make LCA more suited for the designer's needs, see Section 5.1.1, have been developed by scholars without including the designers in the process. However, developing tools to aid the building designers to eco-design requires knowledge on their process and needs, and therefore designers should be included in the development process to truly develop LCA in a direction that is better suited for early stages of building design. Furthermore, scholars developing other ways of conducting LCA validate their tools either against other tools or apply them to case studies. To truly validate the usefulness for designers, the simplified LCA methods should be tested by them. Hence, the fact that this is not found in research is a gap and future work should focus on remedying the situation.

The elimination of gray literature (conference papers, governmental and industrial reports) might mean that some relevant literature has been overlooked. Furthermore, the temporal limitation of the review to the last decade might have eliminated some relevant literature, as eco-design is not a new concept. However, a sufficient amount of literature, with a respectable quality, was found to answer the research questions and thereby reach the objective of the paper.

7. Conclusions

This paper set out to identify and explain by which measures, such as tools and methods, environmental considerations, eco-design, can be included in the building design process and what barriers are hindering implementation in the building sector. It was found, through a systematic literature review, that the main barriers to implementation of eco-design are, firstly, lack of knowledge amongst building designers on the environmental benefits of eco-designing and on how to eco-design a building; secondly, the lack of suitable legislation to provide an incentive for eco-designing; thirdly, lack of suitable tools and method for eco-designing buildings. The tools identified here were life-cycle assessment which, though its ability to assess and quantify environmental impacts, can provide the designer with information on where to focus an eco-design effort, and help quantify the environmental performance of one design solution over another. However, LCA is a very complex tool and requiring data which hinders its uptake in building design. The second tool identified is green building certification schemes which can offer guidance to the designer in terms of a number of criteria to meet and provide benchmarks, so the

designer has something to compare the environmental performance of their design against. However, the schemes currently have a tendency to weigh some criteria over others which can potentially bias the design outcome. In addition to the two tools, nine different eco-design strategies were identified to guide and give the designer a clear aim during design. The strategies focus on energy efficiency, mainly during use of the building, and on reducing material consumption and waste through the entire lifecycle of the building. This article contributes with a comprehensive collection of the tools and strategies for eco-designing buildings while simultaneously identifying the barriers that hinder its implementation in the building sector, seen from stakeholder's perspective. This study thereby provides a novel insight into the necessary developments for tools and strategies to be better in practice and provide future research directions as a potential solution to the identified gaps in research. Firstly, the eco-design strategies are currently focused on either reducing operational energy consumption or embodied impacts (material consumption and waste generation). This focus can lead to environmental rebound effects. Therefore, future research should focus on developing strategies and/or design guidelines that take both aspects into consideration simultaneously for instance, by quantifying the environmental impacts when applying more than one eco-design strategy to a building in a way so both aspects are considered. In fact, quantifying the environmental consequences of applying the strategies alone or in combination with each other can also be a possible solution for the second research gap, how to provide the lacking knowledge for eco-design of buildings. Lastly, it was demonstrated through this review that scholars propose various ways to overcome the features making LCA undesirable for building designers. None of which is tested by actual design teams to validate their usefulness which consequently means that despite scholars' best efforts LCA is still not useful for the designers. Therefore, future research needs to include the designers in the development and let them test the tools.

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