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Indicators for quantifying Environmental Building Performance: A systematic literature review

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ABSTRACT

Buildings as products are complex structures with a long service life compared to most other products and they induce considerable environmental impacts throughout their life cycle. The Environmental Building Performance (EBP) depends on attributes like building design, selection of building materials, building location, as well as operation and maintenance. This article provides the accumulated scientific knowledge on how to quantify EBP by a systematic literature review. Such knowledge is valuable for decision-makers and facilities managers in the process of implementing an environmental strategy and focusing on improving EBP. The review includes 69 articles that cover three research topics relating to EBP: I) indicator categories, II) building types and III) assessment methods. The results show that the environmental impacts are higher for non-residential buildings, and that the building use stage has significantly higher environmental impacts than the other stages. Relating to that, the article identifies eight main categories for quantifying EBP and discusses two methods for assessing EBP.

Keywords: Building performance; environmental performance; energy; facilities management; life cycle assessment

1. INTRODUCTION

The building sector is one of the most resource consuming sectors. The buildings and building construction sector combined are responsible for 36% of global final energy consumption and nearly 40% of total CO_2 emissions [1]. Furthermore, the construction and use of buildings in the EU account for about 33% of water consumption, 33% of waste generation, and more than 30-50% of total material use, depending on the material type [2][3]. In recent years, global use of energy in buildings has grown by 1% per year and global building-related CO_2 emissions continue to rise by nearly 1% per year [1]. Nevertheless, the interest in sustainable development and building performance has been on the agenda since the early 1960's. Nowadays we see concepts and developments like smart buildings, intelligent buildings, green buildings and sustainable buildings, trying to improve the building performance and reduce the negative environmental impacts from the buildings. The overall goal is to create high-performance buildings that accommodate different aspects of sustainability through their life cycle [4]. Some aspects relate directly to the environmental performance, but there are also economic (operational cost, rental cost, asset value) and social (safety, security, accessibility) aspects that must be taken into account to address all relevant building performance assessment dimensions. Even though EBP focuses on environmental dimension of sustainability, it still has strong ties to economic and social sustainability dimensions through e.g. operational costs and indoor climate quality affecting building users' health. The main drivers for optimising EBP are increased focus on climate change related impacts and building energy efficiency, but also economic considerations such as cost reductions on building operation and maintenance (O&M) activities play a role.

The relationship between building life cycle (design/construction/use/end of life stage) and environmental impacts encompasses high complexity since decisions made in the early design stage combined with external parameters like building location (country) and energy supply type (renewable/non-renewable), and later quality of construction work, affect the following impacts from the use and end of life stage.

Studies on building performance in facilities management (FM) have recently been conducted by Ebbesen [5] and Nielsen et al. [6]. However, these articles are lacking a comprehensive identification of studies focusing on indicators for quantifying EBP. Defining specific indicators enables measurement and analysis of actual building performance and provides possibility to benchmark building performance across property portfolio. At the same time, indicators put limits on measurements since each of them focuses on a specific impact parameter, making it alone insufficient to provide a more holistic performance analysis. To resolve this conflict, similar indicators are often grouped into categories that can provide a more general picture of building performance within the given context. This article examines which indicator categories are most commonly used for quantifying EBP. Additionally, the article examines whether residential or non-residential buildings have the largest environmental impacts, and which methods are usually applied for assessing EBP.

2. METHOD

The article at hand aims to provide the accumulated scientific knowledge on how to quantify EBP. To reach the goal, a systematic literature review (SLR) was conducted according to the criteria presented in Okoli & Schabram [7]. A SLR was chosen as research method for analysing the body of knowledge and identifying potential research gaps. The literature was reviewed to identify main building environmental indicator categories and their role in relation to the whole life cycle of buildings. A SLR includes four stages with eight underlying steps: Planning stage (purpose and protocol), Selection stage (literature search and screening), Extraction stage (quality appraisal and data extraction), and Execution stage (analysis and findings, and writing the review).

In the planning stage, the purpose of the literature review was defined as: Identifying indicators and methods for quantifying EBP and determining which building types have the largest environmental impacts. Here, the authors also agreed on a common protocol regarding review procedure including identifying relevant research databases and key words for the study.

In the selection stage, the literature search was conducted using 5 research databases (DTU FindIt, Google Scholar, ScienceDirect, Scopus, Web of Science). The literature search on key words "building environmental indicator" returned 1,125 research articles from 12 international journals. To reduce the amount of results, the scope was further limited in terms of time and topic relevance. The time limitation (2010-2017) was introduced to ensure focus on more recent research, and since the study focuses on buildings, only articles relating to the building sector were considered topic relevant. Introduction of time limitation and topic relevance criteria reduced the number of initially relevant articles to 107 and excluded 4 journals. The subsequent screening of all 107 articles (mainly abstracts) eventually yielded 69 articles on building environmental indicators. These 69 articles (appendix A) constitute the data set of the study.

In the extraction stage, quality appraisal and data extraction from data set was conducted. The data set was categorised in 5 research areas for determination of which building types induce the largest environmental impacts: residential buildings, non-residential buildings, residential and non-residential buildings combined, buildings in general, and other building-related articles.

The choice of research method entails both benefits and limitations to the article. The method entails review of peer-reviewed research articles with focus on EBP, but also ignores relevant research conducted before 2010. Based on the analysis and findings from the execution stage, the work article identifies indicators and methods for quantifying EBP, determines which building types have largest environmental impacts and discloses several research gaps for further studies.

3. THEORY

A building is a combination of components that each induce a set of impacts on the environment. Since a building can be much more complex than the sum of its components, a building should be considered as a unique entity with the main purpose/function to provide occupants with suitable comfort conditions, with a low amount of energy consumption and with a limited impact on the environment [8].

3.1. *Building Performance & Environment*

The interest in quantifying relationships between building performance and environmental impacts emerged already in the early 1960's [9]. Building performance assessment has focus on the behaviour of a building under actual conditions of operation. Building performance assessment is seen as a mean to ensure that a building and its parts meets specific building requirements, and so determine the 'building quality' according to specific assessment criteria [10]. Hence, the assessment of building performance during operation is also used for evaluating the building quality. However, building performance is a complex term because the lack of consensus on what constitutes building performance, covering the overlapping dimensions of social, economic, environmental and technological factors [11]. In the facilities management sector, the European standard EN 15221-7 defines guidelines for performance benchmarking and provides a range of key indicators to identify areas in which there might be a need to improve performance.

Environmental Building Performance (EBP) focuses particularly on environmental impacts from buildings induced during their life cycle. Environmental impacts of buildings are typically summarized in two impact groups: embodied impacts (i.e., impacts embodied in the constructed building) and operational impacts (i.e., impacts occurring over the "active" service life and hence during use of the building) [12], [13]. The environmental building performance depends on attributes such as building design, selection of building materials, quality of the construction work, building location, choice of energy supply source, and O&M activities [14], [15].

Reducing total environmental impacts from a building life cycle is not an easy task, partly because of abovementioned attributes, but also due to the risk of burden shifting that can transfer negative impacts from one building stage to the other. For example, to reduce operational impacts, one can choose to install more thermal insulation or use triple-glazed instead of double-glazed windows, but then again, these solutions will increase embodied impacts since more materials are used for constructing the building.

Once designed and built, it is not easy to change environmentally impactful decisions made in relation to the building design such as building orientation, window-to-wall ratio, and Heating, Ventilation, and Air Conditioning (HVAC) system [16]. The processes used to O&M activities have an even larger cost and environmental impact than the design and construction process [4], [17]. Appropriate building life cycle prediction is therefore an important topic for EBP. Cabeza et al. [18] note that in research, the reference study period ranges between 10 and 100 years, with the majority of articles considering 50 years as reference study period for a building life cycle. Grant et al. [19] argue that study period assumptions contribute significantly to expected environmental impacts, by as much as 4–25% depending on the impact category. These claims are also supported by the comparative study of office buildings in Europe and the United States, wherein maintenance impacts comprised 4–15% of the total impact [20]. Another comparative study of nine building envelope systems concludes that maintenance related impacts may range between 2-55% of the total life cycle impact, depending on the estimated service life, the estimated maintenance regime, and the frequency and intensity of replacement [19].

3.2. Environmental building performance indicators

The evaluation of EBP is usually assessed through Key Performance Indicators (KPIs) grouped into several categories allowing for comparison of different design solutions and monitoring of actual building performance during operation [10]. Such indicators are used to provide aggregated information about a phenomenon in a clear and efficient way [21]. The purpose of an indicator system is "*to provide a measure of current performance, a clear statement of what might be achieved in terms of future performance targets and a yardstick for measurement of progress along the way*" [11]. The use of KPIs and benchmarking is fundamental to any improvement strategy as KPIs reflect a project's goals and provide means for the measurement and management of the progress towards those goals for further learning and improvement [22].

In facilities management, KPIs are popular as they are suitable for monitoring and controlling desired outcomes of existing buildings. KPIs help the FM organisations to focus on potential benefits in relation to the resources spent [23]. However, there is an ongoing debate about what type of KPIs to select and what they are in fact quantifying. For example, there is a vigorous discussion on whether UNEP Benchmarking Think Tank Index measures environmental performance, sustainable performance, service performance (e.g. durability/adaptability) or energy performance [24].

Another issue is selecting the appropriate number of performance indicators. Selecting a single indicator makes the decision easier, but it can also mean a loss of information. On the other hand, a large set of indicators can limit comprehension and the relative importance of each indicator [25]. Thus, defining the appropriate number of effective indicators is important since the quantitative performance results are influenced by the list of indicators. Ideally, there should be a limited number of indicators with standardized measurements that are easily comparable with targets, benchmarks, or other appropriate standards [11], [26].

The environmental performance indicators are usually grouped into several categories. For example, Kylili et al. [22] divided the environmental category into 12 sub-categories, while Toller et al. [27] select six indicators for environmental monitoring of the Swedish building sector. Alwaer and Clements-Croome [11] identified 16 impact categories related to sustainable buildings of which 6 impact categories concern environmental indicators.

3.3. Measuring Environmental Building Performance through indicators

Many assessment tools based on performance indicators have been developed for assessing environmental building performance. For example, Pons et al. [28] have identified 10 environmental impact assessment tools for buildings. Most of them are complex rating tools in which the assessment is made applying certification scheme specific weights to different criteria [16]. Environmental assessment tools show some common features: they are environmentally driven; based on indicators of building performances; and score based [10].

There are two basic assessment approaches for measuring environmental building performance. The first approach is based solely on life cycle assessment (LCA) while the second approach encompasses criteria-based certification tools, which in some cases also rely on an LCA approach. Amongst the most widespread certification tools are BREEAM, LEED, CASBEE, SBTool and Green Globes. They are the multi-criterion systems aiming to cover both environmental, economic and social aspects of sustainability. The tools are easy to understand and can be implemented in criteria specific steps for each criterion. A critical aspect regards the selection of criteria and weight given to each criterion. In the selection of assessment criteria, environmental aspects receive much more attention than economic and social ones. Energy efficiency is always considered the most important category amongst certification tools, followed by indoor environmental quality, waste and pollution. The development of the German DGNB certification tool puts increased focus on the quality of the building, functional aspects, and social integration is more considered than in the other certification tools [29].

Certification tools are well related to market interests and stakeholders' culture [29], but can lead to erroneous conclusions, seen from a scientific point of view [30]. These tools can make it difficult to select relevant performance indicators, and some tools are even accused of lacking vital indicators for assessing building envelope performance such as material efficiency, energy efficiency, economic efficiency and indicators based on life cycle thinking such as life cycle cost and embodied energy [24]. The US National Institute of Standards and Technology analysed the LEED system from an LCA perspective and concluded that it is not a reliable sustainability assessment system [29].

On the other hand, LCA has earlier proven to be an accepted scientific method for assessing environmental building performance [12], [31], [32]. LCA is an internationally standardized method of accounting for all inputs, outputs, and flows within a process, product, or system boundary to accurately quantify a comprehensive set of environmental, social, and economic performance indicators [16]. The fundamental LCA principles and the framework for life cycle assessments are outlined by ISO 14040 and the requirements and guidelines are given in ISO 14044. In addition, EN 15643 covers sustainability assessment of buildings, and EN 15978 provides the basis for the environmental performance assessment of buildings [12].

Although LCA is mainly used during building design, this assessment method can also be related to building operation. In building renovation projects, LCA is for example suitable for comparison of several products, building strategies, or building components that fulfil renovation criteria [33]. LCA can also be used for evaluating environmental building performance across property portfolios. Through the detailed result analysis, LCA can identify the weakest environmental points in buildings and highlight the most environmentally-friendly solutions. There are though several barriers for applying more dynamic LCA in practical building operation. The barriers include the perception that the LCA method is already highly data-demanding and work-intensive, and consequently costly. It is also perceived that the use of LCA building tools requires a high degree of knowledge. Other barriers to the use of LCA in general include prejudices about the complexity, arbitrary results, accuracy and problems regarding the interpretation of results [34]. Furthermore, the application of the LCA method does not guarantee a reduction of emissions or energy consumption, but it highlights weak environmental points of products (buildings) and identifies hotspots for improving environmental performance of products[35].

4. RESULTS

4.1. EBP in a building life cycle perspective

According to EN 15978 [36], the building life cycle covers four stages: product, construction, use and end-of-life (EoL) stage. The product stage covers raw materials supply, transport and materials manufacturing. In the construction stage, building assembly takes place in which building materials are delivered to the construction site, where the construction/installation process is executed. The use stage covers building operation and maintenance period (repair, replacement, refurbishment and operational energy consumption), and in EoL stage building demolition, waste processing and disposal takes place. Benefits and impacts beyond the system boundaries are not covered by the study.

The results presented in Figure 1 show that the research mainly focuses on EBP within the use (34/69) and product (31/69) life cycle stages. The construction stage (25/69) is less related with EBP, while End-of-Lifetime (EoL) stage is least associated with EBP (22/69). Furthermore, the study shows that almost every third article (21/69) covers all four life cycle stages indicating that EBP does not always relate to a specific life cycle stage, but covers the entire life cycle. This result supports earlier findings by Conte & Monno [10] described in theory section 3.2.

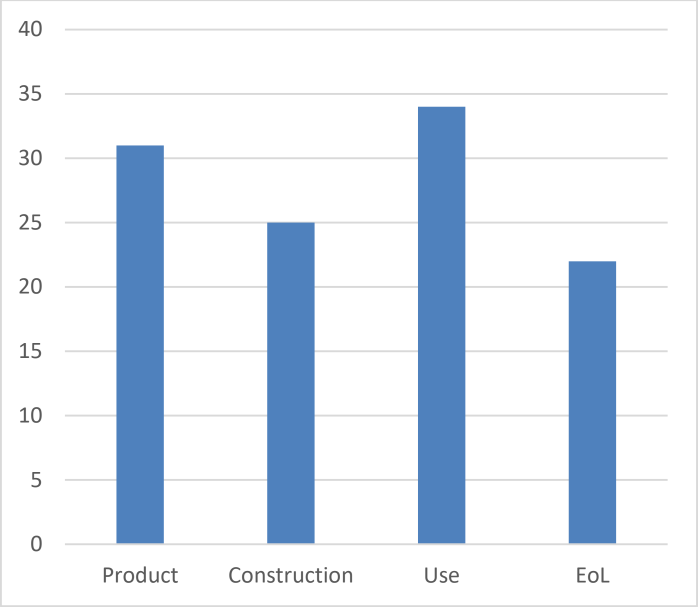

Figure 1: The number of research articles focusing on each building life cycle stage (n=69).

The more sporadic focus on the construction and EoL stages is most likely attributable to the fact that the construction stage is a goal-oriented process mainly focusing on a building assembly, while the EoL stage is often disregarded due to lack of data (also on future systems such as waste processing) or is heavily simplified [37].

On the other hand, most of the research on EBP focuses on the design and use stage. The research relating to the design stage concerns extraction and manufacturing of building materials and components as well as their characteristics in relation to environmental building performance. In relation to the design stage, Basbagill et al. [38] highlight the importance of building's early stage design when determining the environmental impacts of a building. They propose a decision support method based on the integration of building information modelling (BIM), LCA and energy simulation to help designers predict the decisions that most critically determine a building's embodied impact.

The results from SLR show that the building use stage has significantly higher environmental impacts than the other life cycle stages. Nevertheless, these impacts are heavily dependent on the decisions made in the design stage, and the quality of work during the construction process. Furthermore, the actual building operation and maintenance is often different from theoretical simulations in the design stage mainly due to occupant behaviour and leads to a gap between theoretical and actual building performance.

Deeper analysis of the results for the use stage shows that the operating energy of buildings usually accounts for 80-90% of the total impacts, while embodied energy accounts for the remaining 10-20% of the total building impacts. For example, Russell-Smith et al. [16] refer to earlier studies which found that for commercial structures over 90% of the energy consumption across the life cycle and 80% of the carbon dioxide emissions stem from the use stage of the building. Russell-Smith et al. [16] also note that Scheuer et al. [39] earlier found that over 95% of the life cycle energy related impacts in a case study of a new university building stems from the use stage related consumption. Also Asdrubali et al. [40] show that the operation stage has the greatest contribution to the total impact (from 77% for a detached house, up to 85% for an office building), whereas the impact of the construction stage ranges from about 14% (office building) to 21% (detached house). In China, a study of residential buildings found that the direct operative impacts account for 68.4% of the energy consumption, 77.6% of the water consumption, 99.2% of the water pollution emission, 86.4% of the air pollution emission, and 48.4% of the solid wastes emission [41].

Another comparative study of 13 buildings found that commercial buildings have significant impacts on the environment compared to the residential buildings [42]. By comparing variables like building location (country), building type (residential/commercial), life time (year), floor area (m^2) and energy use ($MJ/m^2/50yr$), the study shows that aggregated greenhouse gas emissions ($CO_{2eq}/m^2/50yr$) for commercial buildings can be up to 5,600,000 ton and 5.40 ton for residential buildings. The study concludes that 80–85% of the total energy consumption in the building life cycle occurs during the stage of occupancy. Also Abu Bakar et al. [43] found that the range of

Energy Efficiency Index (EEI) among 73 case buildings from 13 countries is 150-400 kWh/m^2/year (primary) for residential buildings and 250-550 kWh/m2/year (primary) for office buildings, indicating that the EEI values of the office buildings are slightly higher than for the residential buildings covered by the study. According to the researchers, this observation is caused by the different life cycle of office buildings and can be attributed to the fact that an office building generally requires more energy during operation due to high occupation intensity, large electrical load usage and higher energy demand to maintain comfort conditions inside the building compared with the residential building. In terms of office buildings, a study of an office building in Finland shows that the most of the covered impacts are associated with electricity use and building materials manufacturing [18]. Particularly, electricity used in lighting, HVAC systems, heat conduction through the structures, manufacturing and maintenance of steel, concrete and paint, and office waste management are identified as the most impacting activities. Another study on EBP shows that the use of building materials, energy consumption and disposal of waste induces between 12 and 35 times higher environmental impacts in the use stage than the production of building materials stage. Also here the operating energy consumption is highlighted as the main source of negative environmental impact [15].

The results of our study also show tendencies against burden shifting for newer buildings in which many of the environmental impacts are transferred from the operation to embodied energy. For example, Blengini et al. [44] note that for new and low energy buildings, the relative role and the importance of life cycle stages are changing and the embodied energy can be up to 60% of the life cycle energy. Also Russell-Smith et al. [16] observe that the increased awareness of environmental problems has led to changes in the distribution between operating and embodied energy. The energy demand in the building use stage has decreased, but at the expense of using energy-intensive materials with high embodied energy and high insulation capacity. Consequently, the benefit of reducing energy consumption in the building use stage is counterbalanced by increases in the embodied energy [32]. Therefore, the lower the operating energy, the more important it is to focus on the embodied energy and assess EBP from a building life cycle perspective.

The operating energy consumption is heavily influenced by choices relating to building envelope, glazing, thermal mass of building structure, insulating materials, day-lighting and lighting control, natural ventilation and energy-recovery opportunities, and HVAC systems and operational modes such as temperature and air volume control, motors and pump types of control, indoor and outdoor air quality and environmental protection [45]. Another important factor influencing the energy demand is the ratio of the envelope surface and the building volume (m^2/m^3). The surface/volume ratio has a significant influence on the heating energy consumption per m^2 building area and therefore heavily affects impacts from the building use stage [46].

The results emphasise four main measures for improving EBP: (1) energy demand reduction, (2) installation of energy-efficient equipment and low-energy technologies, (3) installation of renewable technologies and electrical systems, and (4) changes in human factors. Nevertheless, the literature also shows that improvement measures have an environmental load in themselves and can have a negative effect on the environment [47]. For example, thicker insulation does not necessarily involve less impact because the impacts induced during the construction and disposal stages might be significant [48]. Neglecting the impacts embodied in the insulation materials may lead to solutions where energy savings might be a compensation for increased environmental burdens elsewhere [49].

Measuring EBP from a life cycle perspective is challenging due to uncertainties relating to the building life cycle. The theory section has earlier emphasised the importance of appropriate building life cycle prediction. However, from the 69 articles used in this SLR, 30 have specified a building life cycle ranging between 20 and 100 years. 33% of the articles specified a building life cycle of 50 years as a reference study period, while 20% considered 100 years as an appropriate reference study period. 10% of the articles use reference study period below 50 years, 27% of articles focus on buildings with estimated life span between 60 and 80 years, and the remaining 10% review and study buildings with different reference periods. These results are consistent with earlier findings by Cabeza et al. [18] and Sharma et al. [42] showing that most research apply 50 years as a reference study period.

4.2. EBP categories and KPIs

The indicators used for environmental performance assessment of buildings are, as described in section 3.2, usually grouped into several categories.

Based on the SLR and findings from the literature, this article proposes eight appropriate EBP categories: *building materials, energy, emissions, Indoor Environmental Quality (IEQ), land/building area use, reuse/recycling potential, waste* and *water*. The eight proposed categories are the result of identified articles within each category and its relative importance for EBP. The energy category is considered most important since it has a direct impact on EBP, but there are also categories like indoor environmental quality and land/building area that affect energy category and thus have a significant impact on EBP. As illustrated in Table 1, each of the proposed categories can include several effective KPIs. The categories in Table 1 are ranked by their importance for EBP as a result of number of identified articles for each category. Some of the categories are interrelated meaning that change in one indicator's performance can have an influence on EBP in other categories.

Table 1: EBP categories and their KPIs

Rank	**EBP category**	**Identified articles (n=69)**	**Examples on KPIs and their units of measurements**
1	Energy	40	Energy consumption (kWh, MWh, GJ) Energy saving potentials (kWh, MWh, GJ or %)

			Energy supply (renewable/non-renewable %)
2	Emissions	36	GHGs i.e. CO_{2e}, NOx, SO_x
3	Water	21	Water consumption (m^3) Water saving potentials (m^3 or %) Water supply – local, rain water (m^3 or %) Water pollution
4	Waste	18	Daily waste (kg, t) Building waste (kg, t) (production, treatment, disposal)
5	Land/building area	13	Property site (m^2) Total building area (m^2) Capacity (m^2/person), Occupancy rate (%)
6	Building materials	10	Aesthetics Durability (years) Thermal properties (U-value) Maintenance properties
7	Indoor Environmental Quality	9	Thermal comfort (^oC) Relative Humidity (%) Daylight Air quality (ppm)
8	Reuse/recycle potential	4	Building components Building materials

The results presented in Table 1 show that Energy and Emissions are the two most dominant environmental indicator categories. Energy is addressed in 40/69 articles, while 36/69 articles focus on emissions. The energy category includes KPIs relating to energy consumption, energy saving potentials, and energy supply distribution (renewable/non-renewable energy). The emission category addresses climate change impacts through the KPIs on emissions of greenhouse-gases such as CO_{2e}, NOx, SO_X etc. Water ranks third and is considered in 21/69 articles. The water category usually includes KPIs relating to water consumption, water saving potentials, water supply, water pollution etc. The waste category is considered in 18/69 articles and uses typically KPIs to show how much daily waste and building waste is produced, treated and disposed. The land and building area use appear in 13/69 articles. The land and building area category focuses on KPIs relating to space management inside and around the buildings, and how efficiently building space is utilized. The building materials are studied 10/69 articles. The building materials category addresses building materials used for construction or renovation of buildings. KPIs for building materials usually cover building material properties such as aesthetics, durability, thermal properties, maintenance properties etc.

The least research focus is on IEQ and reuse potential: 9/69 articles consider IEQ while only 4/69 articles focus on the reuse potential. The IEQ category includes KPIs like thermal comfort, daylight, air quality etc. IEQ indicators are often described as social indicators, but since many IEQ indicators have an impact on EBP, they are in our study considered as an environmental category. Previous studies, mostly focusing on office buildings have shown that the occupants' health and wellbeing can be affected by various indoor environmental parameters, such as temperature, humidity, ventilation, natural lighting or illumination, and noise [50]. The reuse and recycling potential category considers potentials for recycling and/or reusing existing building components and materials for other purposes after their ended lifetime. This category is only considered in 4/69 articles and relates usually to studies in which the whole building life cycle is covered, including EoL stage.

Figure 2 shows the distribution of 69 articles within 5 building research areas on EBP indicator categories. The articles on residential buildings (26/69) are mainly focusing on energy, emissions and waste, while articles on non-residential buildings (5/69) such as commercial and public buildings mostly study energy, water, land/building area use and building materials. Research articles including both residential and non-residential buildings (5/69) focus on energy, emissions, and water and waste. The research on buildings in general (20/69), which typically includes building models and simulations, focuses like research on residential buildings, mostly on energy and emissions. Additionally, it is also notable that the IEQ indicator category is most studied in this research area. Other building-related articles (12/69) covering unspecified building types, building assessment tools and sustainable development agendas show similar tendencies as the literature on four previous research topics, and focus most on energy, emissions, water and waste categories.

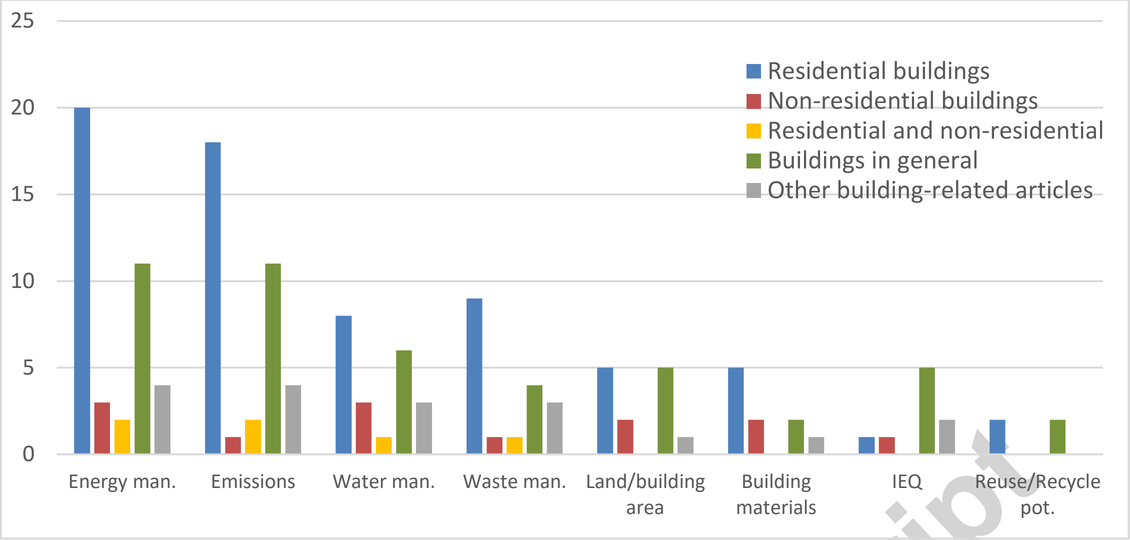

Figure 2: Distribution of 5 research areas on 8 EBP indicator categories (n=69).

Deeper analysis of the results from Figure 2 reveals that most research conducted on EBP indicators relates to energy and emissions categories. The literature study conducted by Abu Bakar et al. [43] shows that the energy consumption in buildings is largely dominated by the HVAC systems, and followed by lighting. A case study of six public buildings with retrofit actions points out that the most significant benefits related to energy savings and reduction of CO_2 emissions are mainly related to the improvement of the thermal insulation of the envelope [51]. This study also concludes that substituting lighting and glazing components provide significant energy benefits. On the other hand, both solar and wind plants involve lower energy savings and higher payback indices than predicted. Moreover, San-José Lombera & Aprea [52] emphasise that the sustainability of industrial buildings should not only be structured around energy consumption, but also include land, water, and material usage.

Results relating to IEQ reveal that if higher comfort expectations are set as a target value, this could have a direct effect on EBP, as a larger consumption of energy by the HVAC systems to maintain comfort expectations is likely to be required [53][54].

The reuse potential is not covered substantially, but there is for example research showing that the recycling of building materials in masonry buildings generates environmental benefits due to avoided impact of virgin material production [55]. Related to reuse potential, Munarim et al. [47] compare building rehabilitation with new building construction and disclose that the construction of a new office building would require about 250 years more to amortise total energy impacts when compared with the rehabilitation and transformation of an old hotel building to an office building. This is due to a very small difference in estimated operation energy consumption between the new office building and the rehabilitated hotel (office) building. Munarim et al. [47] conclude that the reuse of an existing building, through its rehabilitation, conserves natural resources and energy that would be used to build a new building.

4.3. Assessment methods

The results show that the LCA method is a dominating assessment method for assessing EBP. In our study, 34/69 articles apply the LCA method for assessing EBP. The results are in line with the theory section 3.3 claiming that LCA is a widely accepted and applied scientific method for assessing the environmental performance of buildings. The LCA case studies reviewed also confirm that the most impacting stages in a building life cycle are the use stage and the manufacturing of building materials, while construction and EoL stages are much less impacting. In the use stage, energy consumption is the dominant factor of environmental impact [56].

Although LCA is the dominant method for assessing EBP, our study notes several issues relating to the LCA approach. The LCA results depend on the approach used, data quality and the selected reference study period which in practice highly depends on maintenance activities, and may be extended by renovation, restoration or rehabilitation investments [47].

Fouquet et al. [57] recommend prospective scenarios to be used as sensitivity analysis for buildings with long service lives, because assuming current technology and consumption patterns over the next 100 years may be more uncertain. LCA studies reveal for example that energy consumption played a key role for the EBP, not only in terms of quantity consumed but also in terms of the type of energy consumed, highlighting the importance of considering energy grids as dynamic entities [49] [58]. The LCA approach does not guarantee a reduction of emissions or energy consumption, but it allows for highlighting the weak points of production processes and identifying possible improvements of technology and management in the perspective of sustainable development [35].

5. DISCUSSION

This study is based on a systematic literature review of 69 research articles. They form the basis for the analysis. By comparison with systematic literature reviews on other related topics, we argue that the number of articles is sufficient to provide a sound review of the topic.

The results of SLR show that the building use stage is the most environmentally taxing life cycle stage for most buildings. At the same time, the SLR discloses the research gap in defining the appropriate reference study period since the building lifespan in the study ranges between 20 and 100 years. There is, of course, a relationship between material longevity, durability, and the natural differences between material assemblies and components [19], but the use stage is also a variable highly depending on O&M activities. A reliable reference study period is therefore an important parameter that needs to be considered when dealing with EBP. Consequently, there is a need for a more dynamic LCA approach in practice that can illustrate the environmental impacts of different O&M scenarios, and not the conventional, static LCA approach as observed in the study. The integration of LCA approach in facilities management is though not an easy task because of difficulties in obtaining complete inventories for building components, tracking material flows and clearly defining system boundaries. The preferability of certification tools in practice is probably due to their simplicity and check list structure. LCA analyses are more rigorous and time demanding than certification tools and limited to a few specialists [29]. Moreover, existing FM software lacks not only interfacing, but also interoperability and integrations with LCA software.

Another important aspect is the relationship between embodied and operational impacts. The decisions made in the early design stage have a significant influence on the following operational impacts. On the other hand, focusing on reducing operational impacts often cause increased embodied impacts, indicating burden shifting between two life cycle stages. Reducing environmental impacts from buildings is therefore a challenge that needs to be assessed through a life cycle approach.

This SLR provides the accumulated scientific knowledge from 69 research articles on how to quantify EBP. Such knowledge is valuable for decision-makers and facilities managers in the process of implementing an environmental strategy and focusing on improving EBP. When the goal is to improve the EBP, it is essential to have a reliable data management system to ensure that the building performance is monitored and analysed properly. It is advisable to collect the data that easily can be reported as KPIs. The use of KPIs and benchmarking is fundamental to any improvement strategy and can be the right step in improving EBP. Combining KPIs with an LCA approach could provide improved system performance monitoring and deliver new insights on building performance, that later could be used for improving EBP.

6. CONCLUSIONS

The article identifies eight indicator categories commonly used for quantifying Environmental Building Performance (EBP): energy, emissions, water, waste, land/building area, building materials, indoor environmental quality, and reuse/recycling potential. Most research focuses on indicators relating to energy and emissions, while there is least research on indoor environmental quality and reuse potential, indicating research gaps between indicator categories. Keeping in mind internal dependencies between the determined categories, EBP should not only focus on energy and emissions, but also address the remaining categories identified in the article. Moreover, to be able to quantify EBP, we recommend clear definition of a building life cycle and consideration of different operation and maintenance scenarios.

The environmental impacts are generally higher for non-residential buildings than for residential buildings. Furthermore, the building use stage has significantly higher environmental impacts than the other stages, and the EBP differs between older and newer buildings in a life cycle perspective. While older buildings have the highest environmental impact during use stage, newer buildings show burden shifting tendencies towards increased embodied impacts as a consequence of lower operating impacts. Especially older office buildings induce large environmental impacts since they generally require more energy during the use stage compared to residential buildings. Still, most of the recent research focuses on residential buildings, indicating lack of research on EBP in non-residential sector.

There are two basic assessment approaches for quantifying EBP: one based solely on life cycle assessment (LCA) method, another on criteria-based certification tools like BREEAM and LEED. The LCA approach dominates in research while the certification tools are claimed more applicable in practice due to their simplicity and check list structure. We recommend the LCA approach since it is a standardised assessment method that can help decision makers choose more environmentally friendly solutions based on life cycle calculations.

Further studies are required to disclose how many of the identified indicator categories are used for quantifying EBP in practice, especially within non-residential sector. Additionally, we suggest studies on determining how LCA can become integrated in FM practice, and how FM software can support improving EBP.

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APPENDIX A

An overview of 69 articles used in the systematic literature review (SLR).

			Environmental category							
	Publication name	***Reference no.***	***Energy***	***Emissions***	***Water***	***Waste***	***Space use***	***Build. Materials***	***IEQ***	***Reuse pot.***
1	Pons et al. (2012)	[28]	1	1	1	1				
2	Lombera et al. (2010)	[52]	1		1		1	1		
3	Seinre et al. (2014)	[54]	1		1		1	1	1	
4	Abu Bakar et al. (2015)	[43]								
5	Malmqvist et al. (2011)	[34]								
6	Rossi et al. (2012)	[59]	1	1						
7	Thiers et al. (2012)	[60]	1	1	1	1				
8	Gangolells et al. (2011)	[61]	1	1	1	1	1			
9	Basbagill et al. (2013)	[38]		1						
10	He et al. (2013)	[41]	1	1	1	1				
11	Pajchrowski et al. (2014)	[15]	1		1	1	1			
12	Fouquet et al. (2015)	[57]		1						
13	Iyer-Raniga et al. (2012)	[62]		1	1	1				
14	Anderson et al. (2015)	[12]								
15	Soust-Verdaguer et al. (2016)	[13]								
16	Lewandowska et al. (2013)	[58]	1			1	1	1		
17	Proietti et al. (2013)	[35]	1					1		
18	Risholt et al. (2013)	[63]	1	1						
19	Nemry et al. (2010)	[46]	1	1						
20	Blengini et al. (2010)	[44]	1	1						
21	Mwasha et al. (2011)	[24]	1	1				1		
22	Moschetti et al. (2015)	[64]	1	1						
23	Islam et al. (2016)	[65]	1	1	1	1				1
24	Wang et al. (2016)	[66]								
25	Passer et al. (2016)	[32]	1	1						

	Publication name	***Reference no.***	***Energy***	***Emissions***	***Water***	***Waste***	***Space use***	***Build. Materials***	***IEQ***	***Reuse pot.***
26	Oyarzo et al. (2014)	[67]	1	1	1	1				
27	Debacker et al. (2013)	[68]	1							
28	Motuzienė et al. (2015)	[69]	1	1						
29	Passer et al. (2012)	[70]	1	1						
30	Blengini et al. (2010)	[37]	1	1			1	1		1
31	Franzitta et al. (2011)	[8]	1		1	1	1	1	1	
32	Cabeza et al. (2014)	[51]								
33	Häkkinen et al. 2016	[71]	1	1						
34	Lasvaux et al. 2015	[72]	1	1	1	1				
35	Asdrubali et al. (2013)	[40]								
36	Sharma et al. (2011)	[42]								
37	Mateus et al. (2011)	[26]	1	1	1	1	1	1	1	
38	Lamnatou et al. (2015)	[73]								
39	Lotteau et al. (2015)	[31]								
40	Lamnatou et al. (2015)	[74]								
41	Huang et al. (2013)	[50]							1	
42	Russell-Smith et al. (2015)	[16]	1	1	1					
43	Gou et al. (2016)	[75]								
44	Silvestre et al. (2015)	[76]								
45	Hollberg et al. (2016)	[77]								
46	Passer et al. (2015)	[78]								
47	Huedo et al. (2016)	[21]	1	1	1	1				
48	Toller et al. (2013)	[27]	1	1		1				
49	Abanda et al. (2013)	[79]	1	1		1				
50	Russell-Smith et al. (2015)	[80]	1	1	1					

	Publication name	***Reference no.***	***Energy***	***Emissions***	***Water***	***Waste***	***Space use***	***Build. Materials***	***IEQ***	***Reuse pot.***
51	Elle et al. (2010)	[30]								
52	Holopainen et al. (2014)	[53]							1	
53	Alwaer et al. (2010)	[11]	1	1	1	1	1	1		
54	Kim et al. (2013)	[45]							1	
55	Todorovic et al. (2012)	[81]	1						1	
56	Carreras et al. (2015)	[48]								
57	Silvestre et al. (2014)	[82]				1				1
58	Iribarren et al. (2015)	[83]	1	1						
59	Melià et al. (2014)	[56]	1	1			1			
60	Russell-Smith et al. (2015)	[84]	1	1						
61	Balaban et al. (2015)	[85]	1	1	1				1	
62	Napolano et al. (2015)	[55]		1						
63	Kucukvar (2013)	[86]	1	1	1		1			
64	Munarim et al. (2016)	[47]	1	1	1		1	1		
65	Kylili et al. (2016)	[22]	1	1	1	1	1		1	1
66	Mori et al. (2012)	[87]								
67	E. Conte et al. (2012)	[10]								
68	Lasvaux et al. (2016)	[25]								
69	Grant et al. (2012)	[19]								
		Totals	**40**	**36**	**21**	**18**	**13**	**10**	**9**	**4**

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Highlights:

- Eight indicator categories can quantify environmental building performance.
- Literature focuses mainly on energy and emissions categories.
- Older office buildings have the highest environmental impacts during the use stage.
- Newer buildings have increased embodied energy impacts.
- Life Cycle Assessment method quantifies environmental building performance.