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How are indicators in Green Building Rating Systems addressing sustainability dimensions and life cycle frameworks in residential buildings?

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ABSTRACT

The use of tools capable of evaluating the sustainability of buildings throughout their life cycle represents a key point enabling the transition towards a sustainable built environment. To this end, different Green Building Rating Systems (GBRS) have been developed over the last few decades. All of them are voluntary schemes and propose a set of indicators to evaluate the associated impacts of buildings throughout their life cycle. However, it is unclear how GBRS are addressing sustainability dimensions and the life cycle frameworks, and particularly in residential buildings, which are responsible for a great part of these impacts. The aim of this study is to explore, in detail, how indicators in GBRS are covering the three dimensions of sustainability (environmental, social and economic) and the information modules proposed by EN 15978, along the life cycle stages of the building construction process. To do so, eight GBRS were selected and the 387 sustainability indicators included in them were analysed and clustered according to three different classification criteria, namely, sustainability dimension, information modules and stage of the construction process life cycle. The analysis and clustering process of indicators was carried out by a panel of experts in the field of study, with multidisciplinary academic and professional background, throughout an iterative process of four rounds and meetings, which led to achieve a consensus in the findings. The results of the analysis revealed that the environmental dimension is the one that is considered most among the tools, and both the social and economic dimensions require more attention to achieve a good balance. GBRS are more focused on the evaluation of the embedded impacts of the building, since most of the indicators are related to the product and construction stages (A1-A5) and therefore need to acquire a more holistic approach throughout the whole life cycle; the indicators should be considered in the very early design stage (not when the building is in operation), when decisions are made and have more potential to improve the sustainability performance of the buildings throughout its lifespan. It was not possible to cluster one set of indicators as they referred to aspects beyond the EN 15978 system boundary (such as site, transport or domestic waste management), thus highlighting the need for more coherence between a building's life cycle and GBRS frameworks, on the one hand, and the inclusion of new information modules covering the above-mentioned additional aspects, on the other.

1. Introduction

The building sector in the European Union (EU) is one of the those that has the most impact on the environment, since it accounts for 42% of the energy consumed, 35% of the greenhouse gas (GHG) emissions, 50% of the extracted materials and about a third of the water consumption and waste (COM445, 2014). Residential buildings, in particular, are responsible for a great part of these impacts and these percentages are presumably going to increase in the coming years (Eurostat, 2020).

The use of tools capable of evaluating the sustainability of buildings throughout their life cycle represents a key point enabling the transition towards a sustainable built environment, from the environmental, social and economic perspective. To this end, different Green Building Rating Systems (GBRS) have emerged in the last few decades and have since been reviewed from different perspectives (Haapio and Viitaniemi, 2008; Lazar and Chithra, 2021a). The first contribution on GBRS was the development of the Building Research Establishment Environmental

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Method (BREEAM) (BRE Global, 1990) and, from then on, different international organisations, such as the World Green Building Council (WGBC, 1990), the International Initiative for Sustainable Building Environment (iiSBE, 2004a, 2004b) and the Sustainable Building Alliance (SBA, 2009), have contributed with the development of new tools, applicable worldwide. But some of the GBRS have gradually been adapted to specific regions/countries in order to meet their unique and contextual requirements (Lazar and Chithra, 2021a). As a result, the number of GBRS currently put into practice around the world is notable and some of them have even expanded their scope to the urban/neighbourhood context. All these schemes are voluntary and comprise a set of indicators to evaluate the associated impacts of buildings throughout their life cycle, usually organised in topics such as energy, waste, water, transport or land features, within the environmental pillar of sustainability, and other topics within the social and economic pillars.

The literature contains numerous reviews that address the study of the characteristics of the GBRS. With a general approach, Lazar and Chithra (2021a) recently performed a bibliometric mapping of publication trends in the development of GBRS, thereby providing a snapshot of the current situation. Their findings highlighted the most productive authors in this field (Bragança et al., 2010; Mateus and Bragança, 2011; San-José et al., 2007), the usual countries and affiliations, the most cited papers (Haapio and Viitaniemi, 2008) and the most frequent journals and keywords used. However, the first attempt to take a deeper approach to look into the GBRS was made by Haapio and Viitaniemi (2008), who explored the differences between the existing tools in 2008 by classifying them according to general criteria. Since then and as new tools have been developed, more research has been published. Among the most recent literature, Bernardi et al. (2017) analysed the general features of six of the most adopted tools (BREEAM (BRE Global, 1990), CASBEE (IBEC, 2007), DGNB (DGNB, 2018), HQE (HQE, 2016), LEED (US GBC, 2019) and SBTool (iiSBE, 2004b)) and explored the categories included in each tool. Illankoon et al. (2017) analysed the categories considered in eight tools with worldwide coverage (LEED, BREEAM, BEAM Plus (BEAM Society Limited, 2021), Green Mark (Building Construction Authority, 2013), CASBEE, GBI (2009), IGBC (IGBC Indian Green Building Council, 2015) and Green Star (GCBA, 2003)) and found that energy, water and indoor environment quality were the most common. Mattoni et al. (2018) analysed five tools (CASBEE, Green Star, BREEAM, LEED and ITACA (2014)) and defined six common categories of sustainability, energy being the one with more weighting while water was the one with the least. Shan and Hwang (2018) reviewed fifteen tools, including some specific ones for the Asian region, and classified their aspects into seven categories, energy again being the one with more weighting, followed by site and indoor environment. From a different perspective of GBRS, but also with the aim of measuring and manage the level of sustainability, Kylili et al. (2016) focused on Key Performance Indicators (KPI) and conducted a literature review to draw the state of the art in building renovation projects. They also defined a common structure of categories (economic, environmental, social, technological, time, quality, disputes and project administration) and subcategories in order to classify and identify the most frequently employed types of KPIs, and found that the environmental is the most popular category with the focus in energy-related, atmosphere and waste management subcategories.

On the other hand, one of the main concerns regarding the literature is to identify how indicators are addressing the sustainability dimensions. Some efforts have been made to revise research from this perspective. Doan et al. (2017) examined four tools (LEED, BREEAM, Green Star and CASBEE) to assess how the environmental, social and economic, plus institutional aspects were considered in each one of them; their results showed that the environmental one is the main focus in building schemes whereas the social one is emphasised in urban/neighbourhood schemes. In line with the findings of Braulio-Gonzalo et al. (2015), who explored thirteen urban sustainability assessment tools, both studies concluded that economic and institutional factors should be promoted to improve the capability of GBRS. Specifically for the region of India, Lazar and Chithra (2021b) focused on GBRS applied to residential buildings there and found that all three dimensions were well balanced, with a slightly higher weight for the environmental one. Awadh (2017) analysed four GBRS (LEED, BREEAM and two particularly developed for the gulf region, Estidama and GSAS), discussing quantitatively the credit weighting given to sustainability pillars, and found that the environmental issues are the most approached in all them, followed by the social, procedural and economic. Although some efforts have been made to explore the balance of the sustainability dimensions, it seems that results varied depending on the number and type of GBRS included in the study. Hence, a good representation of tools used around the world is needed for analysis, in order to draw general conclusions. Furthermore, few studies considering GBRS specifically applicable to residential buildings were found.

As seen from the previous findings, the environmental aspect reaches a high degree of relevance among the GBRS. The Life Cycle Assessment (LCA) methodology (ISO 14040, 2006; ISO 14044, 2006) and the framework proposed by EN 15978 (2011) are the two approaches commonly used to holistically analyse the environmental performance of buildings (Sartori et al., 2021). So that, the second main concern is to find how indicators included in GBRS are approaching the LCA framework and, in turn, to investigate the role of the life cycle approach in the GBRS framework. Sartori et al. (2021) pointed out the potential of the LCA methodology when evaluating sustainability in buildings and explored the connection between LCA and GBRS. After analysing six tools (LEED, BREEAM, Green Star, HQE, CASBEE and DGNB), they found that while GBRS are mostly based on a checklist with many qualitative criteria, the LCA methodology allows quantitative results to be obtained, which facilitates the decision-making process. Ismaeel (2018) analysed the interrelations between eleven GBRS and LCA through the investigation of midpoint and endpoint environmental impact categories and highlighted discrepancies in the base of their environmental assessment, and then showed the need for a robust base for comparing the outcomes obtained with the two approaches. From a country context perspective, Palumbo (2021) analysed the effect of LCA data sources on a specific Italian tool, and Oviir (2016) analysed the application of the LCA methodology within the framework of an Estonian one together with some others used in the country, showing how each scheme deals with the life cycle of a building and which criteria are given higher priority. Trigaux et al. (2021), with a wider approach beyond the GBRS, analysed various benchmarks developed on the basis of the LCA methodology, and included in their work different models and tools, and some GBRS (BREEAM, CASBEE, DGNB and LEED). They analysed aspects such as the LCA method used, LCA database and inventory, reference units and study time period, geographical coverage, building elements and assemblies considered, and the life cycle modules according to EN 15804 (2012) approached. However, their study only did general investigation and did not reach the level of indicators analysis, in detail.

With the aim of exploring how the stages of the life cycle of the building construction process are being approached by GBRS, which represents the third main concern raised herein, some work has been found in the literature. Ferrari et al. (2022) analysed six GBRS and its engagement with the stages of the building life span (design, production, construction, use, maintenance, demolition and disposal), finding that design, construction, use and maintenance are the most addressed ones, being these in common between all GBRS analysed. However, they did not investigate this engagement at the level of the indicators included in the GBRS. Meex et al. (2018) looked at possible solutions to check the suitability of LCA-based environmental impact assessment (EIA) tools (not specifically GBRS) for use by architects during early design stages, and defined the requirements that these tools should meet; but, they did not investigate if the current GBRS met these requirements through the indicators included. With a focus on building refurbishment, Vilches et al. (2017) showed that the more frequently studied life cycle stages among the literature are those related to production and use phases, exclusively analysing environmental issues, not social or cultural ones. Once more, the analysis is not conducted at the level of indicators.

Based on these literature findings, the shortcomings of both approaches, GBRS and LCA, are evident and the confluence of the two is needed. While GBRS emphasises the improvements and advantages of the design decisions, LCA outputs are focused on quantifying the environmental damage. Additionally, although both methods evaluate a building's environmental impact systematically, LCA focuses on a global or regional context, but ignores the impact of a new building in a neighbourhood or community context, which is considered in GBRS. However, and despite these relevant findings in the literature, none of the studies explored how the stages of the life cycle of the building construction process and the information modules for the different stages of the life cycle of a building proposed by EN 15978 (2011) are being addressed in GBRS, at the detailed level of the indicators. And this is essential to be able to use both approaches in a consistent framework for modelling environmental impacts of buildings.

Furthermore, although good knowledge about GBRS currently exists in the literature, the research conducted was strongly focused on the analysis of the categories/topics considered and the weightings allocated to each one. Also in line with conclusions drawn by Li et al. (2017) in their review and comparative analysis on studies addressing GBRS, the majority of existing work concentrated on general information comparison of the assessment methods, covering only basic information (such as developers, schemes, classification levels, etc.). Meanwhile, only few studies conducted the indicator comparison, which is the most detailed comparison level, and, as they concluded, more attention is required to be paid to this especific analysis. Additionally, and as depicted from the literature review in this work, the analysis of the balance among the dimensions of sustainability and the stages of the life cycle of the building and of the building construction process still seems to be neglected in the literature. To overcome these gaps, this study aims to seek answers to these three main research questions:

- RQ1) Are the three dimensions of sustainability (environmental, social and economic) equitably addressed in GBRS?
- RQ2) Do the indicators included in GBRS consider the information modules for the different stages of the life cycle of a building proposed by EN 15978?
- RQ3) At which stage of the life cycle of the building construction process should the GBRS indicators be assessed to improve a building's sustainability?

2. Methodology

The methodology used in this work consisted of two main phases, as shown in Fig. 1 and described below.

- In Phase I, Green Building Rating Systems (GBRS) were selected, ensuring that they were applicable to residential buildings and covered a wide range of regions around the world. GBRS generally consist of an extensive list of sustainability indicators that measure the level of sustainability regarding different aspects, such as energy, water and waste, within the environmental dimension; environmental awareness, within the social one; or cost of construction, within the economic one. The indicators included in each GBRS were identified, together with a set of common aspects to which the indicators refer, in order to facilitate a subsequent systematic analysis and clustering. The clustering was made as follows: the scheme provided by the GBRS was analysed in detail and the indicators included in each one were reviewed and coded. Although each of them proposes a different structure to group them, similar aspects were identified and a common structure has been proposed, which made it possible to work with a common language in the framework of this study.
- In Phase II, the GBRS indicators were clustered in accordance with three different criteria:

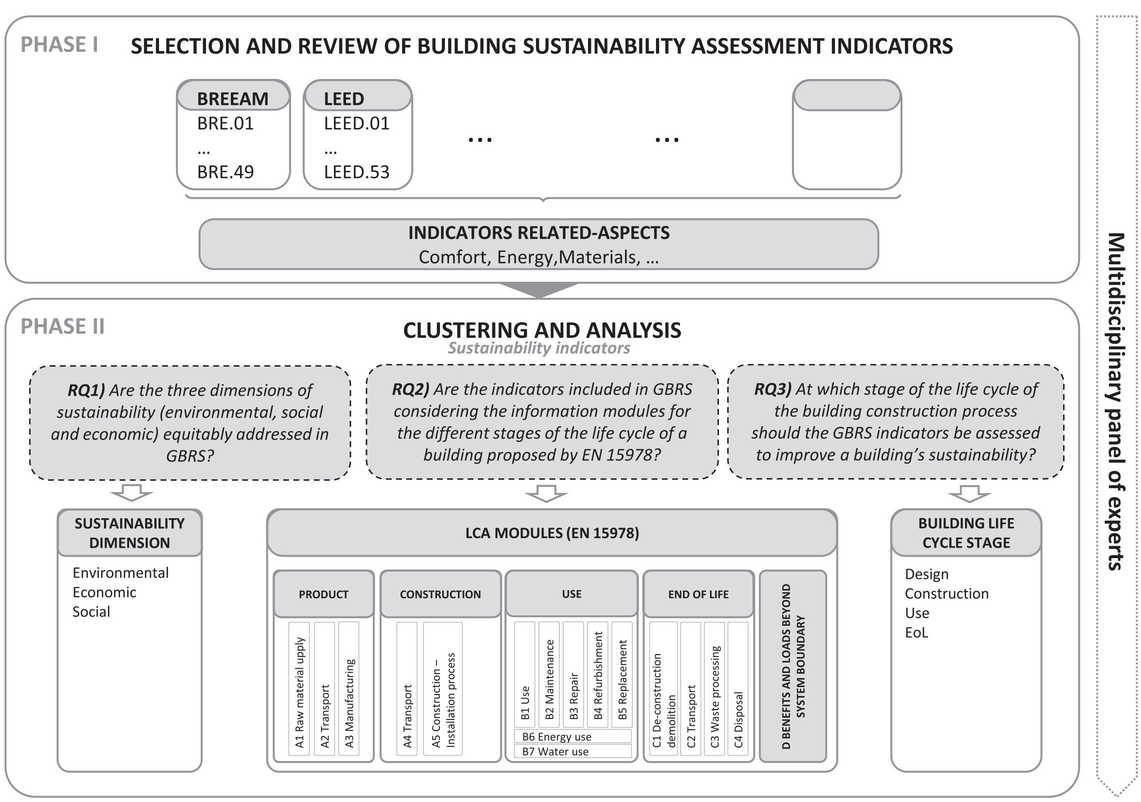

Fig. 1. Methodology

- The sustainability dimension: environmental, economic and social. Since the earliest uses of the term *sustainable development* (Brundtland, 1987), three traditional dimensions or pillars have been assumed to be necessary to achieve sustainable systems: environmental, social and economic. In addition, CEN-EN 15643 (2012) urges inclusion of the three pillars together when assessing a building's sustainability.
- The information modules for the different stages of the life cycle of a building proposed by EN 15978 (2011), based on EN 15804 (2012), which are:
  - product stage (A1-A3): covers the cradle-to-gate processes for the materials and services used in the construction,
  - construction stage (A4-A5): covers the processes from the gate of the factory making the construction products to the practical completion of the construction work,
  - use stage (B1-B7): B1 encompasses, more specifically, the impacts and aspects arising from the normal conditions of use of the components of the building; modules B2 to B5 are related to maintenance, repair, replacement and refurbishment operations; B6 includes energy used by building-integrated technical systems during the operation of the building; and B7 includes all the water used and its treatment (pre- and post-use), also during the operation of the building,
  - end of life stage (EoL) (C1-C4): considers the building's demolition as a multi-output process that provides a source of materials, products and components that are to be discarded, recovered, recycled or reused, and
  - benefits and loads beyond the system boundary (D): considers components for reuse and materials for recycling and energy recovery as potential resources for future use, and quantifies the net environmental benefits or loads resulting from these operations.
- The stages involved in the life cycle of a building: design, construction, use and end of life (EoL) proposed by EN 15978 and the Royal Institute of British Architects Plan of Work (RIBA, 2020):
  - Design stage, which consists of the strategic definition, preliminary studies, concept design and technical design.
  - Construction stage, which corresponds to the manufacturing and construction processes and handover.
  - Use stage, which is defined by the operation and management of the building.
  - EoL stage, which includes the decommissioning of the building, deconstruction, reuse and recycling.

The clustering process was tackled by a multidisciplinary panel of experts from different disciplines and geographical areas, composed by an architect, an environmental engineer and an industrial engineer, whose academic and professional background matched with the field of the study. The review and clustering were carried out in several rounds throughout an iterative process, until achieving a consensus in the findings by the experts. The Phase I was approached in a first round, where one of the experts analysed in detail the set of indicators identified, from her own viewpoint, and classified them according to the aspect to which referred by considering environmental effluents (airborne, waterborne, solid waste, etc.), but also users' comfort and other building users' issues; then the related aspects to indicators were defined in a common structure. This work was revised, subsequently, by the other two experts and, afterwards, a meeting session was taken to discuss discrepancies and bring together the various points of view, until defining the final classification. Phase II was approached in three rounds, following the same latter dynamic, one round for each one of the clustering criteria: the sustainability dimension, the information modules proposed by EN 15978 (2011), the stages of the life cycle of the building construction process. The process of clustering ended when, in the final meeting session after each round, a consensus in the findings was achieved. Following this dynamic, different experts' points of view within the disciplines considered in the study were integrated altogether, which brought objectivity and a holistic vision to the work conducted herein.

3. Results

3.1. Phase I: Selection and review of GBRS indicators

In order to cover a wide range of the world's regions, eight GBRS applicable to residential buildings were selected: BREEAM (BRE Global, 2016), LEED (Leadership in Energy & Environmental Design) (US GBC, 2019), CASBEE (Comprehensive Assessment System for Built Environment Efficiency) (IBEC, 2007), Green Star (GCBA, 2003), Green Globes (ECD, 2019), DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) (DGNB, 2018), VERDE (GBCe, 2017) and Level(s) (the European framework for sustainable buildings) (Dodd et al., 2021). They are briefly described in Table 1 and their geographical distribution worldwide (Asia, Africa, North America, South America, Europe and Australia) is shown in Fig. 2. Some of these GBRS are adapted to specific countries, which develop their own particular GBRS. For instance, Green Star, despite being set up in Australia, was subsequently adapted to South Africa, Brazil and Chile; and LEED was originally from the US, but also applicable in many countries in South America, such as Mexico, Colombia or Peru.

LEED, BREEAM, CASBEE, Green Star and Green Globes are the oldest ones, and have already been widely implemented around the world, both internationally and regionally. DGNB emerged in Germany more recently and has now already been adapted to nearby countries, such as

Table 1
Descriptors of GBRS.

GBRS	Origin	Year	Developer	Applicability	# ind.	Rating system
BREEAM	UK	1990	BRE	UK, US, Netherlands, Norway, Spain, Sweden, Germany, Austria, Switzerland, China, etc. (89 countries)	49	✓
LEED	US	1998	US GBC	US, China, UAE, Brazil, India, Canada, Mexico, Germany, Turkey, Korea, etc. (more than 167 countries)	53	✓
CASBEE	Japan	2004	IBEC	Japan	57	✓
Green Star	Australia	2002	GBC of Australia	Australia, New Zealand, South Africa	65	✓
Green Globes	Canada	2000	ECD	Canada, US	73	✓
DGNB	Germany	2008	DGNB	Germany, Austria, Switzerland, Denmark, Spain	38	✓
VERDE	Spain	2010	GBCe Spain	Spain	39	✓
Level(s)	Europe	2020	JRC	Europe and international	16	

Notes: UK: United Kingdom; US: United States; BRE: Building Research Establishment; GBC: Green Building Council; IBEC: Institute for Building Environment and Energy Conservation; ECD: Energy and Environmental Canada; DGNB: Deutsche Gesellschaft für Nachhaltiges Bauen; JRC: Joint Research Centre; UAE: United Arab Emirates.

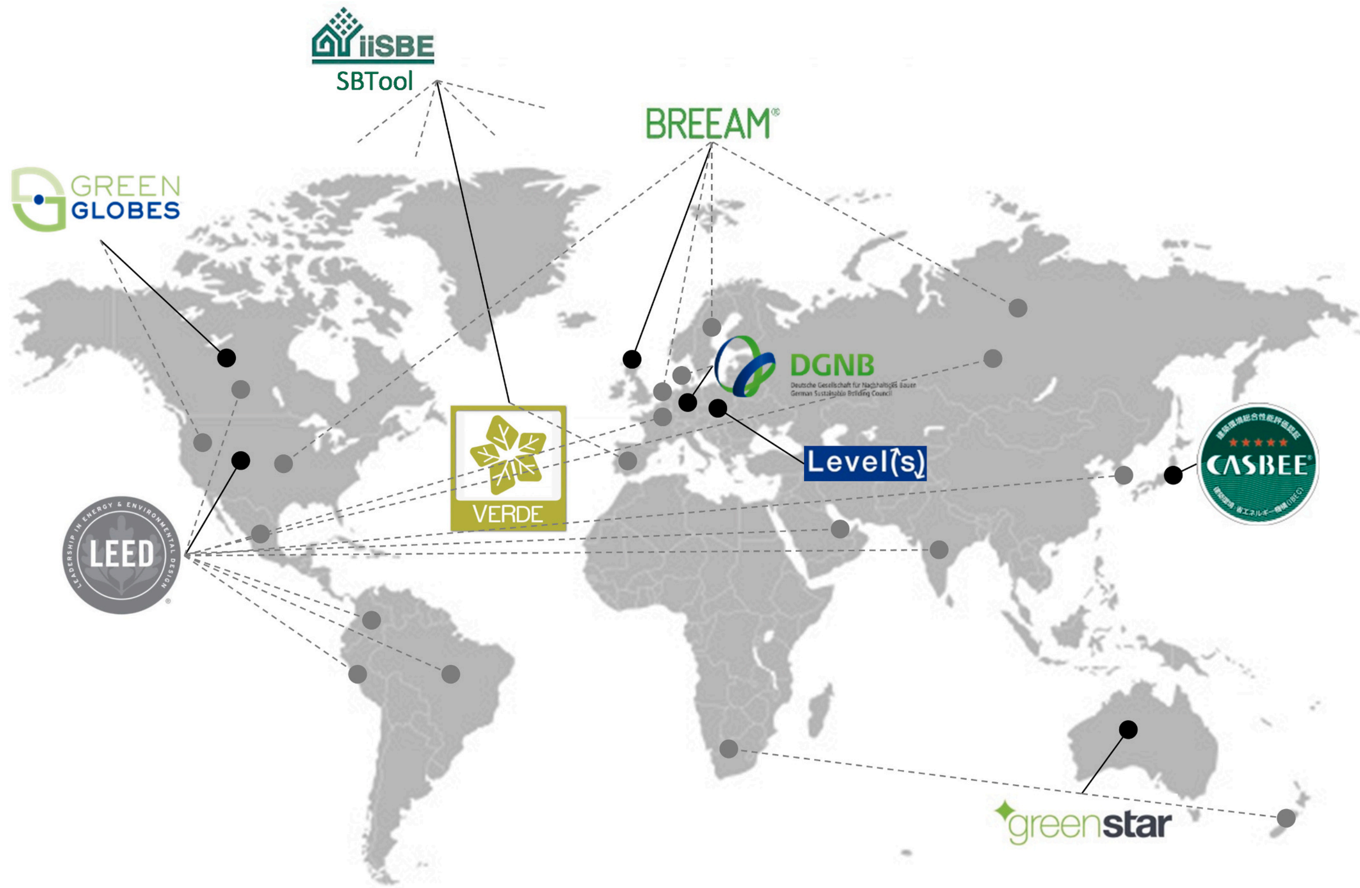

Fig. 2. World map for applicability of selected GBRS.

Austria, Switzerland, Denmark and Spain. The tool VERDE was also developed more recently and it derives from the SBTool (iiSBE, 2004b), which was created by the iiSBE with the aim of providing a generic tool to be adapted to the context specificities of the corresponding region where it is to be applied. In this case, VERDE is the adaptation to Spain, and it was selected in this study as a representation of the SBTool. Finally, Level(s) is the youngest tool and, although it was developed by the European Commission, it is intended to be applicable internationally. It has the minimum numbers of indicators, with maximum leverage to deliver sustainability, and integrates a common language for building sustainability. Because it was developed only recently, Level(s) has received very little attention in the literature (del Rosario et al., 2021; Díaz-López et al., 2021; Sánchez-Cordero et al., 2019) and its inclusion in the study contributes to enhancing the background.

The scheme provided by the eight GBRS was analysed in detail and the indicators included in each one were reviewed and coded, 387 altogether. The Supplementary material provides an exhaustive list and the codes of the indicators included in each GBRS. Although each of them proposes a different structure to group them, similar aspects were identified and a common structure has been proposed, which made it possible to work with a common language in the framework of this study. The common aspects identified are the following: Comfort, Energy, Environmental awareness, Materials, Natural resources and climate change, Waste and Water. Table 2 describes the items considered in each aspect.

The indicators included in the GBRS were classified according to these aspects, by considering their objective. Fig. 3 shows, graphically, the distribution of the 387 indicators in the seven aspects, by GBRS. It can be observed that Comfort is the most addressed aspect (with 108 indicators dedicated to it), which denotes that the user's well-being is a priority among the GBRS; this is followed by Natural resources and climate change (with 107). To a lesser extent, the aspects Waste (with 25) and Environmental awareness (with 20) are also evaluated. On average, the weight by number of indicators conferred by the GBRS to each aspect is 28.5% to Comfort, 27.9% to Natural resources and climate change, 12.3% to Energy, 10.9% to Materials, 8.5% to Water, 6.9% to Waste and 5% to Environmental awareness. It should be noted that the GBRS are quite balanced among the aspects and coincide with these percentages. From the perspective of GBRS, only Level(s) fails to cover one of the aspects, Environmental awareness, since it does not include any related indicator.

3.2. Phase II: Clustering and analysis

3.2.1. Sustainability dimension

The indicators were classified according to the three dimensions of sustainability -environmental, social and economic- and the results are presented in Fig. 4. The vertical axis represents the number of indicators in these three dimensions, each of which is one bar. The percentages included in the bars represent the proportion of indicators (in number) in each GBRS (colours) that addressed each dimension; so that, Fig. 4 depicts, in horizontal interpretation, how the indicators are quantitatively distributed according to the three sustainability's dimensions, and by GBRS. For instance, LEED distributed 65% of its indicators according to environmental dimension, while 25% and 10% according to social and economic ones. It should be noted that some indicators addressed more than one dimension; for instance, some included in Comfort were classified both as environmental, due to their being related to pollutant emissions (VOCs, formaldehydes, etc.), natural ventilation, lighting and noise protection, and as social, because they are also related to the well-

Table 2
Indicator-related aspects.

Aspects	Items considered
Comfort	Proximity to public transport and services
	Indoor environmental quality (VOCs emissions, etc.)
	Thermal comfort
	Ventilation
	Lighting
	Noise
	Privacy
	Efficiency of spaces and accessibility
Energy	Energy demand and consumption
	Improvement of building's thermal envelope
	Charging electric vehicles
	Renewable energy
	Efficient household appliances and building facilities
	Energy consumption monitoring
Environmental awareness	Environmental education
	Good practices user guide
	Code of conduct for contractors
	Accredited professional involvement
Materials	Use of recycled materials
	Use of materials obtained from sustainable resources
	Use of local materials
	Impact of construction materials and eco-labelling
	Conservation of the building
	Design for adaptability and renovation
Natural resources and Climate change	Habitat management and restoration
	Land use and reuse
	Mitigation of the ecological impact during construction
	Use of vegetation to create shade
	Flood and erosion risk
	Urban Heat Island effect
	Atmosphere emissions (CO_2, NO_x, etc.)
	Responsible use of refrigerants
	Transport and car parking
	Pollution mitigation (water, soil, lighting, etc.)
Waste	MSW segregation
	MSW storage in the building
	Composting
	CDW management
	Planning a selective demolition strategy
	Recycled aggregates
Water	Drinking water consumption
	Irrigation system
	Sustainable water treatment
	Reuse of non-potable water
	Water consumption monitoring

Note. VOCs: Volatile Organic Compounds; CO_2: carbon dioxide; NO_x: nitrogen oxides; MSW: Municipal Solid Waste; CDW: Construction and Demolition Waste.

being of the building's occupants. This is also the case of indicators addressing transport and mobility: despite being mainly related to such an environmental issue because of the associated pollution and GHG, they also relate to the social pillar, since they enhance the users' comfort.

Fig. 4 evidenced that the Environmental dimension is by far the most addressed by the GBRS; in fact, the tools dedicate 68.3% of the indicators to it, on average. The Social dimension, however, represents 25.8% and the Economic one accounts for only 6%. The Economic dimension is covered by six GBRS, but with a very low percentage of indicators: Level(s) (13.6% of indicators related to the Economic pillar), DGNB (12.5%), LEED (10%), VERDE (5.9%), Green Globes (4%) and BREEAM (1.8%). Among them, there are some kinds of indicators related to the cost of construction, energy efficiency measures for saving on utility bills, building users' guide (with monetary saving strategies) and consideration of the life cycle cost assessment.

3.2.2. Information modules for the different stages of the life cycle of a building

The indicators included in the GBRS have been clustered according to the information modules for the different stages of the life cycle of a building proposed by EN 15978 (2011) and the results are depicted in Fig. 5. Module B1 integrates the highest number of indicators (117), mainly related to indoor air quality, natural ventilation and lighting, and low emission materials, and thus they are linked to the aspect Comfort and user's well-being. Subsequently, and in order of relevance, there are modules A1-A3, B6, A5, B7, A4 and D. This implies that GBRS confer special relevance to the product stage of the building (A1-A3), when construction products and components are manufactured, from cradle to gate. A total of 88 related indicators were found in this case. The energy consumption during the use stage (module B6) is quite relevant, with 85 indicators. The construction and installation processes together with the transport activities involved in reaching the workplace, modules A4 and A5, clustered 53 and 77 indicators, respectively. Maintenance operations during the use stage (B2-B5) to ensure that the building is well preserved also gained importance among the tools, refurbishment standing out from the rest with 49 indicators. The EoL stage (C1-C4) was found to be the least addressed, which denoted that considering the deconstruction of the building is not a priority among the tools. It can therefore be said that the tools are not focused on planning what to do with the building at the end of its useful life, waste being understood as an opportunity in favour of the Circular Economy principles (The Ellen MacArthur Foundation, 2012). Finally, module D agglutinated 51 indicators.

From the GBRS perspective, the following should be noted: VERDE does not address modules B2-B4; modules C1-C4 are not addressed by BREEAM and Green Star; DGNB, Green Globes, CASBEE, Level(s) and LEED are well aligned with the modules proposed by EN 15978 since they are all covered.

However, 58 of the indicators included in the GBRS could not be classified since they are not aligned with any of the modules proposed by EN 15978, thus going beyond the standard. These were clustered in item X in Fig. 5 and are presented in Table 3. As seen, aspects related to the Building site and planning, Transport and mobility, Building design, Solid waste management, Water pollution and management, Nature and biodiversity, Environmental awareness, As-built documents of the project and Stakeholders are out of the system boundary of the standard. Particularly, indicators related to transport, mobility and proximity to public services and facilities, and promotion of bicycle use should be noted, as they are recurring and widely included in the tools and, in fact, they represent an important impact on a building's sustainability; however, they are not considered at all by the standard. The same occurs with the great amount of solid waste generated by a building's users during the use stage, which is not considered in the scope of EN 15978. These aspects and the others presented in Table 3 should be highlighted and taken into consideration to ensure a holistic approach when conducting an LCA of buildings. The tools with the highest number of unclassified indicators were LEED (12.4%), VERDE (9.8%), Green Star (9.7%) and BREEAM (7.9%), which means that they go beyond the standard's system boundary.

3.2.3. Stages of the life cycle of the building construction process

The results of this clustering are presented in Fig. 6 and, as can be seen, the design stage agglutinated most of the indicators among the tools (58.4% in average), which indicates that it is at this point in the project – briefing and conceptual and technical design – when decisions should be made to truly improve the sustainability of the building. The design stage is followed by the use stage (with 31.6% of indicators, on average), the construction (7.3%) and the EoL (2.8%). So, although the use stage is the one that has the greatest environmental impact on residential buildings (Nemry et al., 2010), acting here is, in fact, too late. Actions should be carried out during the design of the building to ensure positive reductions in the environmental impact of the life cycle of the

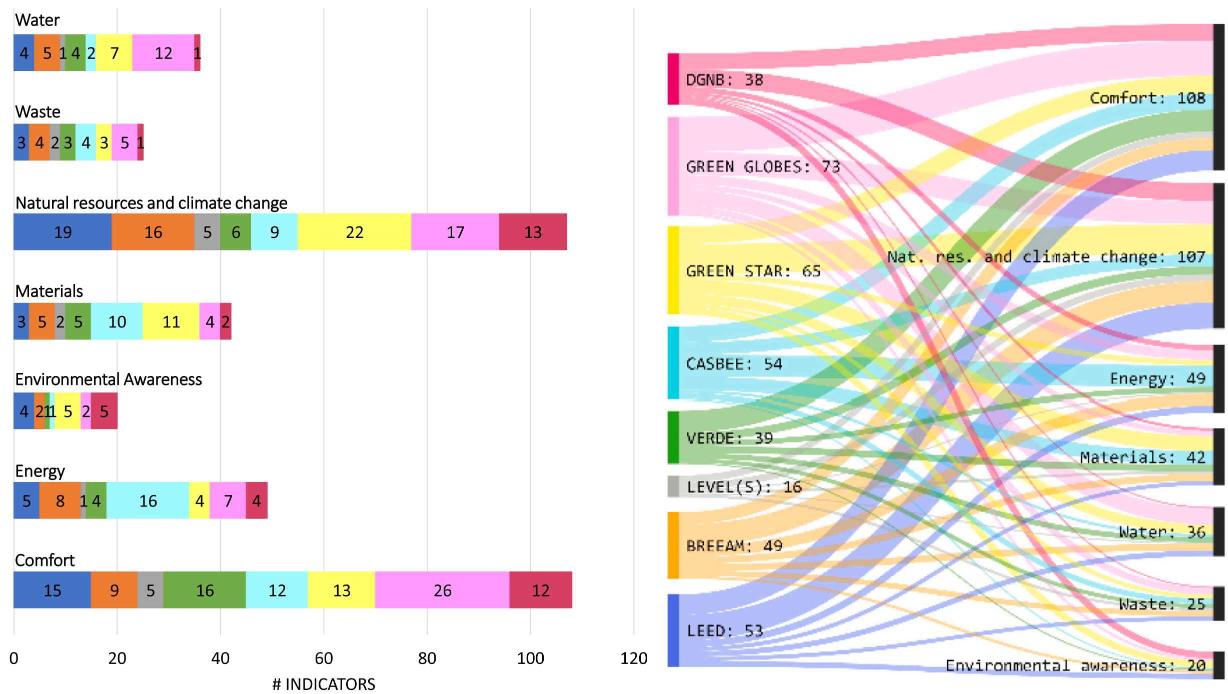

Fig. 3. Identification of common aspects in GBRS indicators and counting.

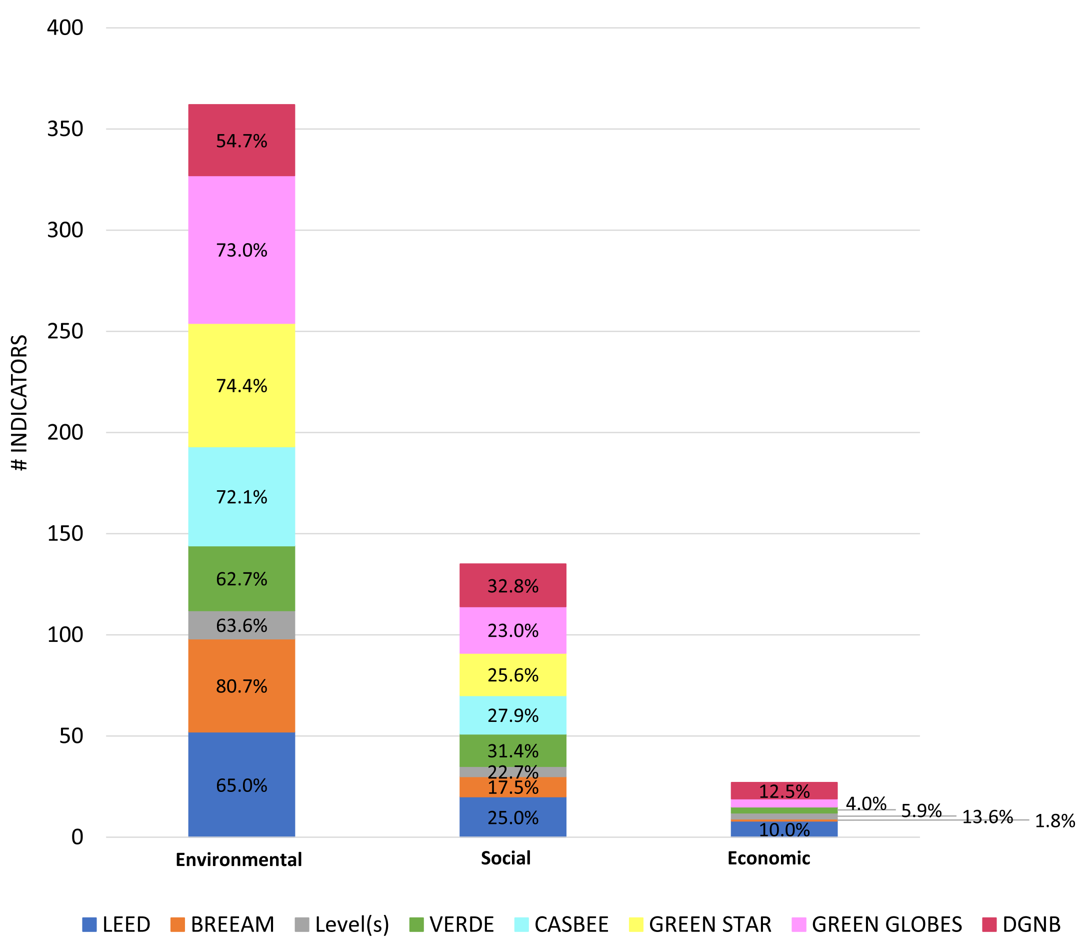

Fig. 4. Clustering: sustainability dimension.

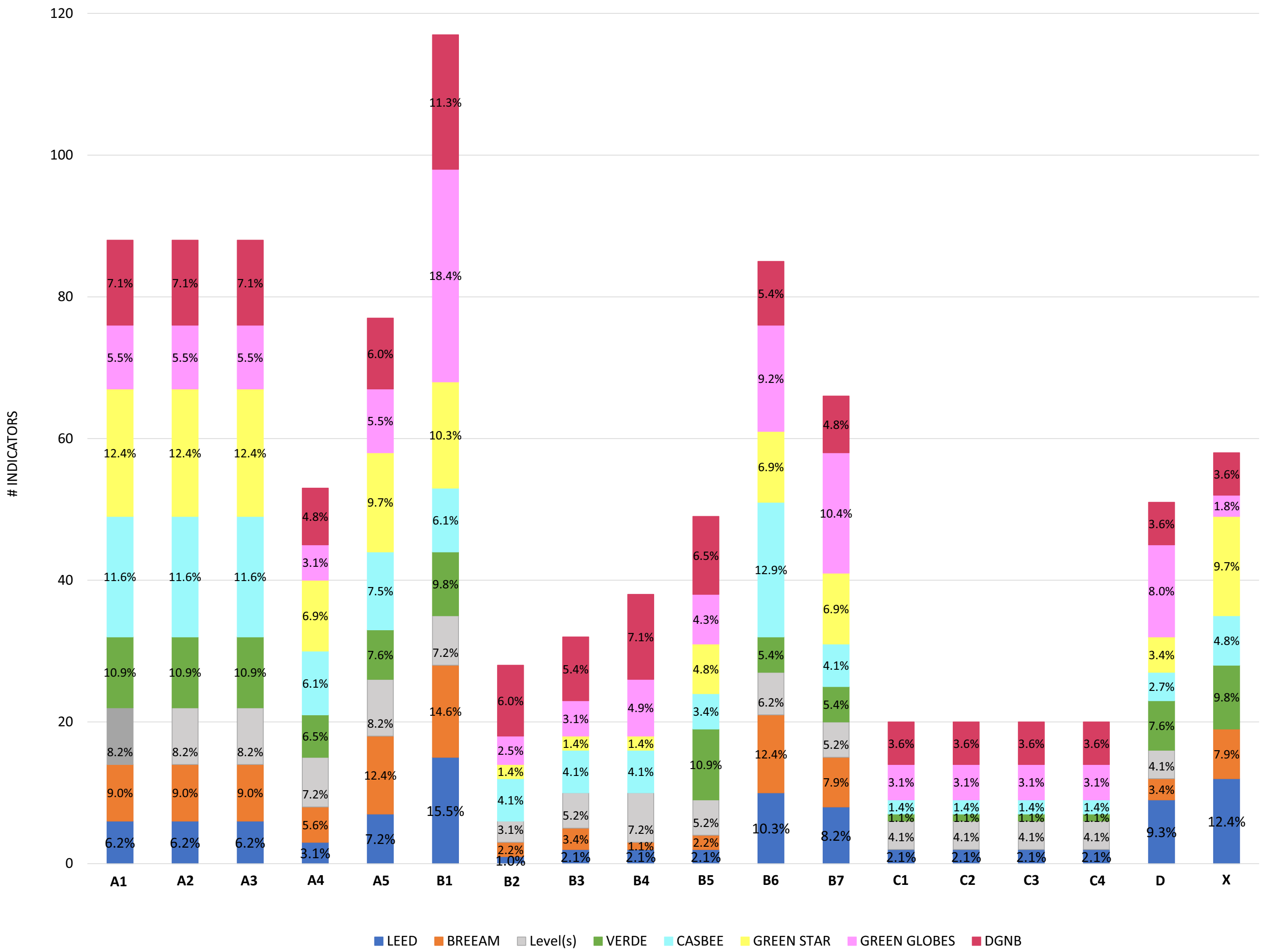

Fig. 5. Clustering: Information module according to EN 15978 (2011).

building by applying the LCA methodology.

4. Discussion

Fig. 7 presents a global overview of connection flows among the 387 GBRS indicators analysed through a Sankey diagram. Despite this overview was made from a qualitative perspective, it connects the 387 indicators with all aspects analysed in this study, at the same time: the sustainability dimensions (environmental, social and economic), the information modules proposed by EN 15978 (2011) (A1-D and X) and the stages of the life cycle of the building construction process (design, construction, use and EoL), providing global information. Taking this view into account and the results obtained in the previous section 3 from the clustering, the answers to the three research questions stated at the beginning of the study could be outlined and discussed, as follows.

In relation to RQ1) Are the three dimensions of sustainability (environmental, social and economic) equitably addressed in GBRS?, the clustering in Fig. 4 and the connection flows in Fig. 7 showed that the Environmental dimension is the most considered among the tools and the indicators mainly focused on aspects related to Comfort, Natural resources and climate change, and Energy. The Social and Economic dimensions are barely addressed. Particularly, CASBEE and Green Star did not include any Economic indicator, and for the rest of the tools, the average percentage of indicators is only 5.97%. This denotes that the Economic aspect should be integrated with more emphasis. In the case of Level(s), it represents 13.64%, including one indicator to incorporate LCC assessment. The Social dimension, despite being more present in the GBRS, represents only 25.75%. The tools that integrated it with more emphasis are DGNB, VERDE and CASBEE.

Regarding RQ2) Are the indicators included in GBRS considering the information modules for the different stages of the life cycle of a building proposed by EN 15978?, from Fig. 5 and Fig. 7 the following findings can be noted:

- Module A. As for the product stage (A1-A3), the tools with the highest numbers of indicators are Green Star, CASBEE and VERDE, including indicators related to the promotion of materials with environmental labelling (ISO 14021, 2006; ISO 14024, 2018) or EPD (ISO 14025, 2006), local and/or sustainable materials, and LCA calculations. As regards the construction stage, module A4 related to the transportation of materials to the site is addressed by all the GBRS, but with less emphasis than A5, which is related to impacts during the installation process. Here, BREEAM includes a notable number of indicators (11, representing 12.4% of the total).
- Module B. B1 is the most addressed, clustering on average 11.7% of the indicators among the GBRS. Green Globes, LEED and BREEAM are the ones that stand out from the rest. This module is related to Comfort indicators. Modules B2-B5, related to maintenance, repair, replacement and refurbishment, are poorly addressed. DGNB and Level(s) are the ones that do include specific indicators in these modules, such as Design for adaptability and renovation, Design for deconstruction, reuse and recycling, and LCC assessment during the

Table 3
Indicators not included within the EN 15978 boundary (clustered as X in Fig. 5).

Aspect	Indicator	BREEAM	LEED	CASBEE	Green Star	Green Globes	DGNB	VERDE	Level (s)
Building site and planning	LEED for neighbourhood development location		●						
	High priority site		●						
	Surrounding density and diverse uses		●						
	Regional priority		●						
	Consideration of the townscape and landscape			●					
	Safety and security of the region			●					
	Control of the burden on the local infrastructure			●					
	Influence on the district						●		
Transport and mobility	Proximity to public transport	●	●		●	●	●	●	
	Proximity to equipment and services	●			●		●	●	
	Bicycle facilities		●		●			●	
	Reduced parking footprint		●						
	Sustainable vehicles and fuel-efficient transport	●	●		●		●		
	Provision of parking spaces for cars				●				
	Office at home (working from home)	●							
Building Design	Comprehensive project brief						●		
	Procedure for urban and design planning						●		
	Performance & Green Design Goals					●			
	Integrated design process					●			
	Access to private open spaces				●			●	
	Right to privacy							●	
	Efficiency of spaces							●	
	Private space	●		●					
	Precautions against crime								
	Size and layout of rooms			●					
	Barrier-free design			●					
	Innovation		●		●				
Solid waste management	Segregation of solid waste	●	●		●			●	
	Composting of domestic waste	●							
	Post occupancy solid waste recycling					●			
Water pollution and management	Watercourse pollution				●				
	Discharge to sewer				●				
Nature and biodiversity	Greening of the premises			●					
	Ensuring the biological habitat			●					
	Preservation of the existing natural environment			●					
	Wildland-urban interface site design					●			
Environmental awareness	The building as an educational tool							●	
	User communication						●		
As-built documents	Custody of project documentation							●	
Stakeholders	LEED accredited professional		●						

use stage. However, VERDE did not include any indicators of this type. These modules are the least frequently included in the LCA of buildings. B6, energy consumption during the use stage, is the second most addressed module. Every tool includes several indicators for it, but CASBEE, BREEAM, LEED and Green Globes stand out above the average. B7, water consumption during the use stage, is also addressed by all the tools but with lower intensity. Here, Green Globes, LEED and BREEAM stand out.

- Module C. The EoL stage is poorly approached, since on average, tools only include 1.7% of its indicators in C1-C4. Moreover, BREEAM and Green Star do not include any indicators of this kind. The indicators that are included in C1-C4 are mainly related to construction and demolition waste (CDW) management. Level(s) is more focused on this issue with indicators such as Design for deconstruction, reuse and recycling. It should be noted that, although circular economy principles (The Ellen MacArthur Foundation, 2012) are gaining importance, GBRS are not currently prepared to adopt them.
- Module D. All the tools include some indicators related to benefits and loads beyond the system boundary, such as renewable energy production, water and energy saving strategies, the use of recycled materials or the reuse of existing buildings or land, among others. It can be observed that notable relevance is granted to this module, with 5.5% of the indicators.
- In general, as depicted in Fig. 5, most of the indicators are clustered in modules A1-A5 and B1, which denotes that GBRS are more focused on evaluating embodied impacts of the building, rather than evaluating the whole life cycle. However, it is suggested that tools with an integrated life cycle approach should be developed and, in this line, it is observed that Level(s) and DGNB, despite having fewer indicators (16 and 38, respectively), are the more balanced ones, with a similar number of indicators dedicated to all information modules. This denotes that both have been conceived with a life cycle approach in the right direction.
- On the other hand, it should be noted that a significant number of indicators (58) do not refer to any of the information modules for the different stages of the life cycle of a building. This shows that EN 15978 does not consider aspects such as the site of the building, users' mobility, solid waste management, water pollution, biodiversity and the environmental awareness of users and stakeholders, which are also important and really impact on the building's overall sustainability. This issue should be reconsidered and studied in greater depth in order to align both the GBRS and the LCA frameworks better and to achieve the optimum sustainability performance levels of buildings. This brings to the fore the need for a wider life

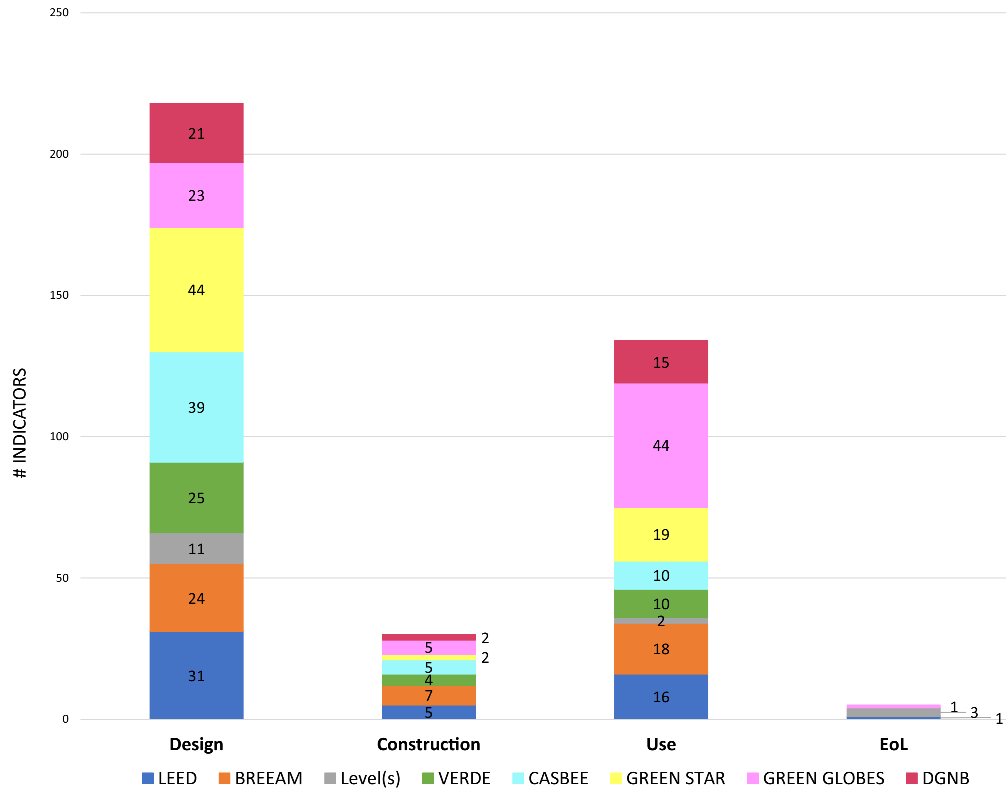

Fig. 6. Clustering: stage of the life cycle of the building.

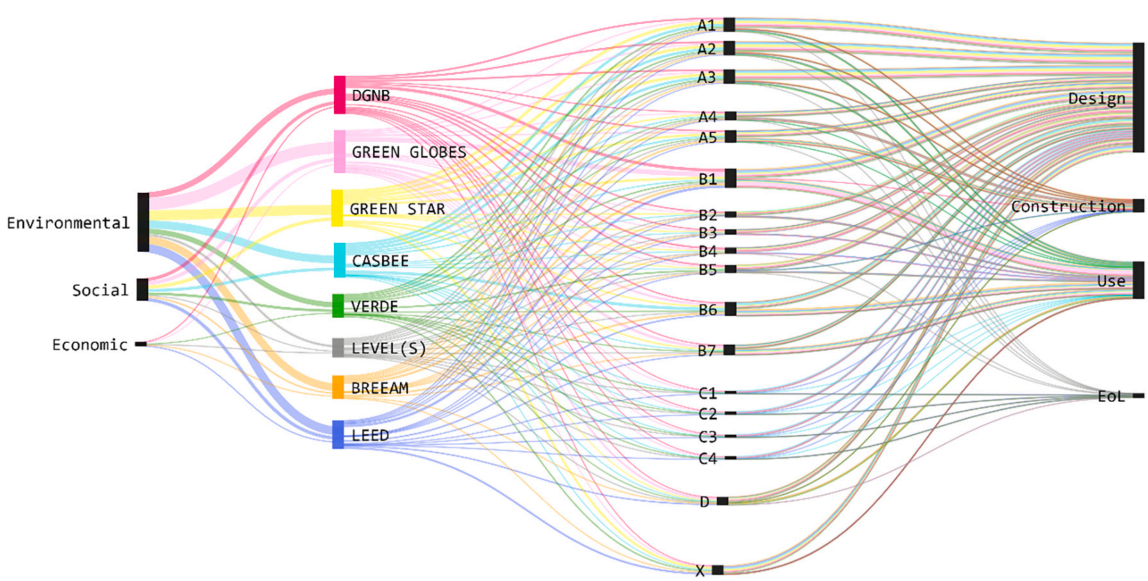

Fig. 7. Sankey diagram showing connection flows among GBRS indicators.

cycle framework approach that could be addressed with the creation of new information modules covering the aspects mentioned above.

Finally, as for RQ3) At which stage of the life cycle of the construction process of the building should the GBRS indicators be assessed to improve a building's sustainability? Fig. 6 and Fig. 7 clearly showed that the Design stage is the most important one to be addressed in order to ensure buildings have lower impacts throughout their lifespans. However, the LCA methodology is recently being applied in the building process, when the building is already constructed and there is no room for improvement. This is why the need to implement the LCA methodology in early stages becomes especially important, that is, in the first conception of the building design.

Among the indicators that should be considered in the Design stage, we found the most relevant ones to be those related to selection of the site; the proximity of the building to public transport and services to reduce the need for a private vehicle; the building's orientation to reduce the energy demand later during the use stage; materials selection (for instance, thermal insulation of the building envelope); provision of storage spaces for bicycles in order to promote their use by the building's occupants; provision of spaces for domestic waste storage to ensure good waste management rates; and the inclusion of renewable energy systems. If these types of indicators are not taken into account during the design stage, it will be difficult to later contribute to reducing the environmental impact during the subsequent stages of the building's life cycle. CASBEE, Level(s), Green Star and VERDE are the ones that place more emphasis on the Design stage of the building.

5. Conclusions and further research

This work has presented an in-depth analysis of the indicators included in the GBRS applicable to residential buildings worldwide and their relationship with the information modules for the different stages of the life cycle of a building established in EN 15978, with the stages of the life cycle of the building construction process and the three sustainability dimensions. It was identified that GBRS are more focused on the evaluation of the embedded impacts, rather than being designed with a holistic approach throughout the whole of the building's life cycle, since most of the indicators are related to the product and construction stages. Information modules related to maintenance and refurbishment activities (B2-B5) are addressed to some extent, as are EoL modules (C1-C4). Hence, more consistency is required among the GBRS in order to comply with a robust and balanced life cycle approach. For this reason, it is recommended that new indicators addressing these information modules should be developed. In this sense, Level(s) and DGNB are distributed quite proportionally among the information modules, despite having a reduced number of indicators.

On the other hand, a non-negligible number of indicators (58) could not be clustered since they referred to the urban context surrounding the building, such as the site, mobility and biodiversity; resource management, such as domestic waste management and water pollution; or environmental awareness of users and stakeholders. These aspects are beyond the EN 15978 system boundary but, in fact, they have an influence on the environmental, social and economic sustainability of the building under evaluation. The inclusion of new information modules addressing these issues should be considered in future revisions of the standard.

In fact, the two building environmental frameworks are pertinent and aligned in the same direction, but they should be more integrated and can learn from each other.

Furthermore, the aspects most commonly addressed by GBRS are Comfort and Natural resources and climate change, which denoted the high importance granted to environmental issues and human well-being, both related to the environmental and social dimensions of sustainability. The economic dimension has thus been left aside and requires more attention. The study also revealed that the LCA methodology is usually applied when the building is already built and comes into operation. However, from the detailed analysis of indicators, this should be integrated in the early stage of the project, that is, the design, when decisions are made and have more potential to improve the level of sustainability performance of the buildings throughout their lifespan.

This study was conducted by a panel of experts composed by an architect, and environmental engineer and an industrial engineer with a wide and solid background in environmental and building's sustainability issues, who shape up a multidisciplinary work team that integrated together the disciplines approached within the review and the clustering process of indicators. This process was carried out in several rounds throughout an iterative process, until achieving a consensus in the findings by the three experts. Although this represented a strength of the study, due to the thorough revision done, it should be noted that it could be, at the same time, a limitation, since the review process was made, inevitably, under the viewpoint of experts. This means that a certain degree of subjectivity could be included, naturally associated with the work done by people.

The results of this work can serve as a starting point to establish greater coherence between the building's life cycle and GBRS frameworks, and can help set improvements and common efforts in their approaches in further work. Also, other building types can be explored in further work.

CRediT authorship contribution statement

Marta Braulio-Gonzalo: Project administration, Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. **Andrea Jorge-Ortiz:** Investigation, Resources. **María D. Bovea:** Funding acquisition, Methodology, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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