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Bibliometric Review of Building Material Assessment for Energy Efficiency in Urban Digital Twins

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***Abstract:** The construction sector exerts detrimental environmental impacts on natural ecosystems. Mitigating these impacts and reducing pollution necessitates the adoption of an assessment tool. During the design phase, decisions must factor in building typology, materials, construction techniques, dimensions, functions, and contextual considerations. Crafting solutions that effectively address all these facets presents a formidable challenge.*
The European Union (EU) advocates for employing the Life Cycle Assessment (LCA) methodology to evaluate environmental impacts in the construction industry. This approach encompasses the entire lifecycle of a product, encompassing production, usage, and disposal stages. However, integrating additional elements such as the urban context and digital twin technologies remains intricate. Given the impending need to enhance energy efficiency in the European building stock through extensive redevelopment, this research aims to identify a robust methodology for selecting optimal building materials. This review seeks to offer an updated perspective encompassing the choice of eco-friendly building materials and the incorporation of digital twin technologies, which facilitate real-time building assessments.
By amalgamating insights derived from this analysis, this research strives to contribute to a holistic framework that addresses the multifaceted aspects of sustainable construction. Such a framework would streamline the selection of environmentally conscious building materials while harnessing the potential of digital twin methodologies for rapid and precise building evaluations. Ultimately, this research aspires to bridge critical gaps in sustainable practices within the construction sector, aligning with the EU's overarching objectives of promoting greener and more efficient built environments.

***Keywords:** Multicriteria Analysis, LCA, Material Characteristics, Sensors.*

1. INTRODUCTION

In Europe, the construction sector is accountable for a substantial portion of energy consumption (42%) and greenhouse gas emissions (35%), while also contributing to half (50%)

of the aggregate building material consumption. Globally, concrete production involves an enormous utilization of resources, including 20 billion tons of aggregates, 1.5 billion tons of cement, and 800 billion tons of water. Buildings, spanning their entire life cycle, sustain considerable environmental effects. The requisite action involves deliberate decisions aimed at ameliorating the persistent ecological impacts associated with the construction phase, thereby fostering sustainability across the entire operational lifespan of the built environment [1-2].
Aligned with the global target of achieving zero consumption by 2050, developed nations must prioritize upgrading a minimum of 50% of their existing building stock by 2030 [3]. Scientific inquiry, notably oriented toward climate change and reinforced by the United Nations (UN) - specifically, the Intergovernmental Panel on Climate Change (IPCC) - underscores the critical importance of simulating building performance concomitant with predicting adaptive design models.
The escalating emphasis on the green building sector, propelled by the aspirations of the 2030 Agenda, is driving an increasing demand [4]. UN member states are equipped with decision support tools (DSS). The European Union's (EU) strategy to attain climate neutrality by 2050 finds its embodiment in the European Green Deal [5].
For instance, in India, the adoption of the Energy Conservation Building Code (ECBC) establishes baseline standards for energy efficiency. Within the construction sphere, the assimilation of ecologically sound practices - including the integration of green technologies - underscores meticulous energy and natural resource management, spanning from building material production to energy conservation and waste management [6-7].
In the endeavor to combat pollution on a communal scale [8], the sector directs its efforts toward technological research in thermal-acoustic insulation. Fostering sustainability and embracing a circular economy involves the integration of synthetic building materials with those sourced from agricultural waste, aligning with principles of eco-friendliness [9].
Mitigating environmental impacts associated with building materials mandates the adherence to sustainability principles across all phases of their life cycle. During the end-of-life stage of buildings [10], Italy's "Criteri ambientali minimi" stipulate measures for material reuse or recycling.
This research initiative stems from the essential need to discern the most feasible and universally accepted assessment methodologies for enhancing the energy efficiency of the building stock in accordance with the ambitious objectives outlined for the year 2050.

2. DATA ANALYSIS

The methodology initiates by conducting an extensive review of existing evaluation and analysis methodologies. This review aims to pinpoint the specific criteria and indicators that are pertinent to the given case study.

The organizational framework of the study commences with the creation of a comprehensive database housing bibliometric data. This database undergoes a rigorous filtering process, resulting in the extraction of a fundamental subset of documents [12]. These documents are garnered in response to the research inquiry, tailored to facilitate a comprehensive multi-criteria analysis focusing on building materials.

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Table 1. Dataset

QUERY	WOS	SCOPUS
"Building materials*" AND "multicriterial analysis".	3-14-15-16]	.3-16-17]
"Building materials" AND "Agenda 2030" AND "criteria"	-19-20]	-19-20-21-22]
		.:11

By querying the WoS and Scopus search engines, the foundation is laid for the construction of a comprehensive database, aimed at providing an impartial response to the research objectives. The outcomes of these queries (as presented in Table 1) are amalgamated while eliminating duplicate entries, resulting in a unified database within the R-Studio environment [23], encompassing a total of 11 scholarly articles. Through the utilization of biblioshiny [24], a trilateral Sankey diagram is utilized to illustrate the interrelationships among Keywords, Titles, and Authors within the cited references, specifically focusing on the ten most extensively investigated subjects. This graphical representation serves to illuminate the intricate multidimensional fabric of research endeavors within the academic domain (Figure1). Subsequently, a meticulous categorization of the data is conducted, delineating it into qualitative, quantitative, and integrated classifications.

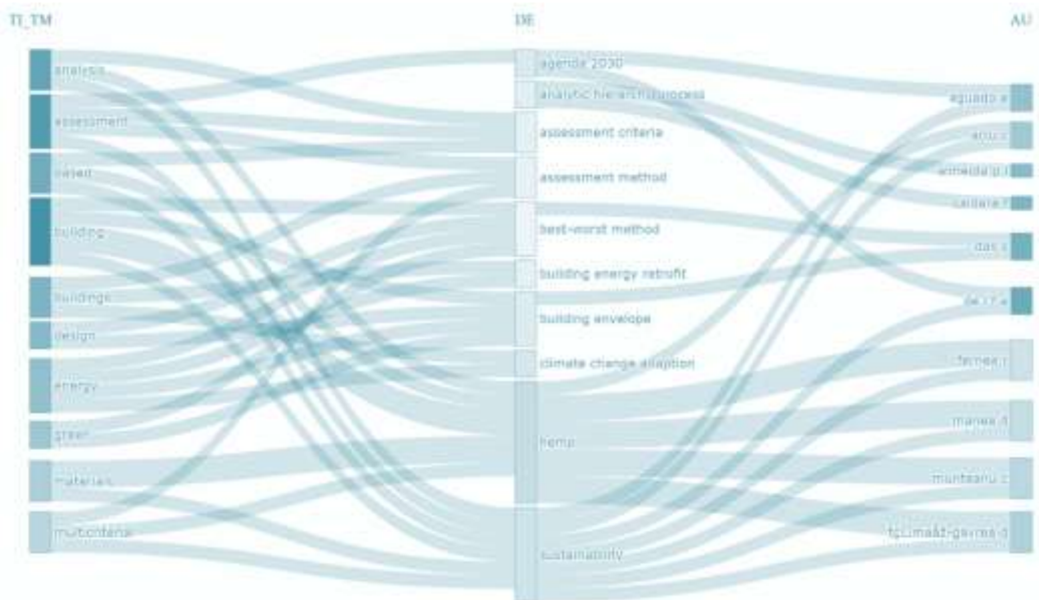

Figure 1: A three-field Plot (Sankey diagram) of Keyword, Titles and Authors of publication of the cited references for the ten most researched topics.

2.1 Quantitative/Qualitative Evaluation Multi-Criteria

Sustainable building policies should exhibit adaptability to factors including climate, culture, building traditions, industrial development levels, and the characteristics of existing built

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heritage [25]. In the context of a multi-criteria analysis, which encompasses the selection of criteria and the corresponding assignment of weights, alignment with the strategies outlined by the European Union (EU) and the United Nations (UN) is indispensable.

An exemplary instance of best practice is the COST C8 project, conceived to aggregate and scrutinize data concerning sustainable advancements in construction science across Europe. This initiative seamlessly integrates methodologies for environmental assessment, construction materials, and technologies for both novel constructions and the preservation of extant building heritage. The project's support to local authorities is harmonious with broader objectives in the realm of sustainable development.

Within Slovenia, the voluntary ZKG quality label for sustainable construction stands as a noteworthy endeavor. This label meticulously addresses specific technical attributes, production process quality, workforce training, innovation levels, economic considerations, and the global environmental footprint. The methodological framework of assessment encompasses diverse spheres, including architectural design, urban planning, structural integrity, material selection, HVAC systems, electrical installations, and building physics. Each criterion undergoes evaluation through quantifiable and/or descriptive indicators, culminating in a weighted matrix that quantifies sustainability impacts [14].

The Analytical Hierarchy Process (AHP) analysis, encompassing five distinct steps, serves to derive consistent sets of relative weights and criteria. This process relies on empirical data and expert evaluations [27]. The AHP methodology, grounded in a hierarchical criteria structure for alternative system selection, has been effectively applied in qualitative field research settings. For instance, it was employed in selecting optimal flooring systems for pig breeding operations, encompassing considerations of economic feasibility, technological efficacy, animal welfare, health, and the overall farm environment [17]. This approach is particularly valuable when faced with the need to evaluate divergent criteria, such as animal welfare versus economic viability, guiding technological decisions.

Researchers have also harnessed the MIVES multi-criteria approach to compare beams constructed from various materials. This method facilitates both qualitative and quantitative evaluation via weighted indicators (ranging from 0 to 1), established through databases and expert consultations. The ensuing scenarios generate graphs that offer insight into sustainability indices, providing a foundation for validation and comparative assessments [22].

2.2 Lca (Life Cycle Assessment) and Multi-Criteria Analysis

The concept of "building life cycle" encompasses the entirety of interconnected phases associated with a structure, spanning research, design, testing, production, transportation, utilization, repair, modernization, renovation, maintenance, demolition, and decommissioning [28]. Life Cycle Assessment (LCA), a pivotal evaluation methodology, involves the aggregation of data into input, qualitative-quantitative, and output categories. This comprehensive analysis, coupled with an assessment of environmental impacts, covers the entire lifespan of the system under examination.

When conducting an ecological evaluation of building materials, the scope extends beyond the building's lifecycle. It encompasses the manufacturing and transportation methodologies of materials from the factory to the construction site, in addition to considering criteria relevant to pre-production phases [29]. These criteria are evaluated on a scale of 1 to 5, based on surveys

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directed at stakeholders involved in the process. This methodological approach, implemented in Poland in accordance with national regulations and EU directives, necessitates the case-specific selection of criteria. It's worth noting that the significance attributed to production and material transportation phases doesn't hold the same weight as subsequent phases for stakeholders [16-30-31].

2.3 Bim/ Fuzzy Bwm Multi-Criteria Analysis

Building Information Modeling (BIM) serves as a comprehensive tool for bolstering the evaluation process across all phases of building development, commencing from the initial design stage [32]. Noteworthy scholarly endeavors [33] have aimed to delineate a multi-criteria methodology within the BIM framework. This methodology encompasses project-specific criteria and extends to considerations encompassing energy efficiency, maintenance, and the judicious selection of building materials tailored to distinct climatic zones.

Within this paradigm, the digital model is meticulously reconstructed within the BIM environment, building upon the foundation of original drawings. This environment facilitates targeted work on a prototype building. Augmenting the BIM library involves the seamless integration of any absent elements. Subsequent to this, energy simulations are executed to gauge the ramifications of initial design choices, incorporating factors such as building morphology and orientation [34]. The consequences of material selection and maintenance practices are methodically assessed, and scores are attributed along a graduated scale from 1 to 5 [35]. The criteria are subjected to deliberate weighting using the fuzzy Best Worst Method (BWM) [36]. This intricate process not only facilitates the evaluation of ecological construction risks but also encompasses data normalization across disparate units of measurement and the assimilation of emerging indicators like building material packaging and material availability. Ultimately, an assembly of domain experts undertakes the evaluation of criteria pertinent to energy efficiency, maintainability, and material accessibility. This evaluation employs a pairwise comparison methodology to ascertain the relative significance of each criterion [35].

2.4 Rhino/Grasshopper/Energyplus/Mcda

In a parallel study, conducted by different researchers [19], a comprehensive assessment of the building was conducted within a virtual environment. The research team opted to employ the Rhino/Grasshopper/EnergyPlus software suite, complemented by a multi-criteria decision analysis (MCDA) framework. To aid in climate and building quality evaluations, the CitySim tool, built upon the Grasshopper platform, was harnessed. The M-MACBETH technique was then employed to determine the weights associated with the various criteria. This approach facilitated the integration of parameters that inherently lacked direct comparability. The process involved an iterative graphical representation [37], culminating in a visual representation with scores ranging from 1 to 100.

Owing to the unavailability of comprehensive weather data, the study exclusively relied on the EnergyPlus data. Throughout the evaluation, the software applications facilitated criterion measurement, each using its respective units of measurement. However, the study highlights the need for further discourse and clarification in the context of measurement units and their comparability.

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2.5 Standardization and Voluntary Guidelines

Standardization and voluntary guidelines serve as integral mechanisms for establishing technical specifications across products, services, and processes. Utilizing voluntary standards to define material qualities through shared protocols enables the selection of materials based on considerations of quality, safety, and reliability.

Among the extensively studied natural-origin materials, hemp-based products stand out, renowned for their eco-friendliness owing to their adeptness at carbon dioxide retention and remarkable insulating properties [38].

Within the exploration of hemp-based insulation materials, a synthesis involving volcanic rocks is performed, followed by a 28-day drying phase. Laboratory analyses encompass acoustic, thermal, and mechanical characterizations of the materials [13]. Acoustic characteristics, including sound absorption coefficients, are determined experimentally using the transfer function method, leveraging acoustic impedance [39]. The thermal conductivity coefficient is identified through the thermo-flowmeter technique [40]. Mechanical assessments encompass the evaluation of compressive and flexural strength [41]. Specimens measuring 40x40x160 mm undergo periodic force application at intervals of 3, 7, 14, and 28 days. The results obtained are subsequently compared against prior investigations [9].

In the context of two case studies involving new constructions with dry frames, a group of researchers [20] applied the UNI (Italian National Unification) method. The initial phase involved the application of the UNI 8290-1 standard to categorize technological units, thereby defining the construction system and identifying predominant building elements [42]. This method also appraised material installation [43] and assessed recyclability indices using percentage-based evaluations.

Furthermore, heightened attention to safeguarding built heritage, driven by conflicts, environmental crises, and social movements, has led to the adoption of spatial detectors as a solution. These detectors are categorized as PIR (passive infrared) detectors, which monitor temperature variations, and MW (microwave) detectors, sensitive to alterations in reflected electromagnetic radiation and movement within the monitored area. Precise installation is imperative to ensure detection efficacy in challenging conditions and facilitate maintenance [44]. In the scope of research [16], parameters essential for evaluation using the EN 50131 methodology [45] were identified. These encompass parameters such as slow test passage, flow rate, detection angle, and sampling.

2.6 Best Practices

Finally, in the context of the United Arab Emirates, a unifying legislative framework might not be feasible, yet an exemplary practice has emerged. Commencing with the Estidama evaluation, a school building underwent transformation into a sustainable campus. This involved the incorporation of three distinct systems: a green wall, photovoltaic panels, and gray water recycling. Guided by the adopted methodology, criteria were developed encompassing the design process, natural systems, and water conservation through recycling. The outcomes of this initiative have yielded a noteworthy exemplar of best practice [21].

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3. RESULTS

The assessment criteria applied to buildings have evolved from a primarily technical approach, primarily focused on estimating energy consumption and resource utilization [46], to a comprehensive multidisciplinary perspective that incorporates various dimensions, including economic-social sustainability [47] and the broader societal implications [48].
In these research efforts, the temporal element has been intentionally omitted, with experts and stakeholders being engaged during the initial phases of transitions [14-17-22].
In recent years, the practice of conducting multi-criteria analyses has been augmented by the integration of relevant software and tools [22-18-19]. A central figure in this context is Building Information Modeling (BIM), which offers a suite of tools that facilitate the evaluation of Life Cycle Assessment (LCA) [22-16] as well as energy efficiency [18-19-21], utilizing values derived from conducted assessments [9-13-20-16] (refer to Table 2).

Table 2. Results

ARTICLE	OBJECTS	METODOLOGY	RESULTS
[14]	residential stock	Aspects: technical, functional, artistic, aesthetic. Seminars and interviews	matrix-weighted calculation
[17]	building materials for animal psycho-physical well-being	Analytical hierarchy process (AHP)	matrix-weighted calculation
[22]	ding materials	MIVES LCA	ix-softwares
[16]	Planned building development	LCA procedure Answers to experts	Weighted calculation
[18]	ıo building	BIM/fuzzy BWM	ix-softwares
[19]	ıo building	Rhino/Grasshopper/ CitySim/ EnergyPlus/ M-MACBETH	vares
[9-13]	Material characteristics/ Test performing	ISO 10534-2:2002 EN 12667:2002 EN 196-1:2016	values for software calculation
[20]		UNI (11277:2008)	

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	Circular Construction Process		e in %
[16]	Sensors	EN 50131	based on the case study and requests
[21]	Introducing 3 systems to the buildings	Energy efficiency	practice

4. CONCLUSIONS

The study demonstrates that by following the methodology prescribed in the reference standard, it becomes feasible to discern the criteria essential for making optimal selections of building materials. The findings obtained from material testing serve as the bedrock for subsequent analyses conducted within the BIM environment, employing dedicated software and tools. These computational resources directly leverage extensive global databases to facilitate the calculation of various criteria, including aspects like material transportation and emissions.
The notion of a digital twin can be elucidated as a prototype building equipped with sensors. The evaluation of specific cases and the procedures undertaken adhere to unified regulations, ensuring a coherent and standardized approach throughout.

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