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An evaluation of digital capabilities to enable a sustainable built asset industry: Developing a Consolidated Sustainability Matrix to inform digital use cases and practices

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ABSTRACT

Current digital capabilities supporting the achievement of sustainability goals in the built asset industry tend to focus on isolated aspects such as energy simulation or emissions tracking. This limits the broader application of digital tools and workflows, namely Building Information Modeling (BIM) and Digital Twins (DT), to support achievement of a comprehensive set of sustainability goals across environmental, social, and economic dimensions. One of the many issues hindering this broader perspective is the lack of holistic understanding of how digitalization can enable sustainability in the built asset industry.

The research presented in this paper introduces the Consolidated Sustainability Matrix (CSM), a unified framework that synthesizes 189 indicators from 25 certification schemes and 26 standards into 15 categories. Using a four-phase methodology, BIM and DT capabilities were mapped against these indicators. To enhance methodological rigor, two complementary metrics were proposed: a Cumulative Weighted Score (CWS) that accounts for respondent expertise levels, and a Weighted Agreement Score (WAS) that quantifies consensus among participants.

The findings reveal that advanced digitalization, particularly sensor-enabled federated models and comprehensive digital twins, can support a considerable number of environmental indicators, especially energy, emissions, and indoor environmental quality management. However, current digital tools show limited support for social and economic sustainability indicators, revealing significant gaps in these areas.

The study makes three key contributions: first, the CSM provides a harmonized framework linking sustainability indicators with digital capabilities; second, the CWS and WAS metrics offer robust methods for evaluating digital tool applicability and expert consensus; third, the research presents the first systematic assessment of how BIM and DT can transcend isolated applications to enable integrated sustainability management. These findings provide actionable guidance for industry practitioners and policymakers while identifying critical research and innovation priorities needed to advance digitalization toward more balanced and comprehensive sustainability outcomes in the built asset industry.

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1. Introduction

The built asset industry is a cornerstone of global economic development, providing essential infrastructure and housing [1]. At the same time, it remains one of the most resource-intensive and environmentally impactful sectors, accounting for approximately 34 % of energy-related CO_2 emissions and over 32 % of global energy demand, with embodied carbon contributing nearly 18 % of total sectoral emissions [2]. Addressing these challenges requires a fundamental shift toward sustainable construction practices, ensuring that environmental, social, and economic considerations are integrated into all phases of a project's lifecycle [3].

To guide this transformation, the United Nations' Sustainable Development Goals (SDGs) establish global ambitions for responsible resource management, climate action, and inclusive growth [4]. However, while the SDGs set overarching sustainability targets, they do not provide specific, measurable criteria for assessing sustainability at the built asset level [5]. Certification schemes and sustainability standards respond to this need by defining concrete assessment indicators [6]. Yet, their implementation in practice remains fragmented and complex, as criteria vary in scope, methodology, and applicability across regions and asset types [7]. This has resulted in a narrow operationalization of sustainability, often limited to select environmental indicators such as energy or carbon modeling, while broader social and economic aspects remain overlooked [8].

Digitalization offers a pathway to address these challenges. Building Information Modeling (BIM) has established itself as a central tool for data-driven decision-making across the building lifecycle [9], with 6D BIM framing sustainability as a dedicated dimension of use cases [10,11]. However, BIM models are largely static and lack adaptability to real-time operational changes [12]. Digital Twins (DT), by contrast, extend these capabilities through continuous data integration, predictive analytics, and feedback loops [13], enabling dynamic monitoring [14] and optimization of sustainability performance [15]. While BIM and DT have been individually applied to tasks such as energy simulation [16], carbon footprint analysis [17], or indoor air quality monitoring [18], existing studies tend to focus on isolated applications rather than on a comprehensive evaluation of how digital capabilities can operationalize sustainability across a broader range of indicators [19].

The study presented in this paper addresses this gap by developing a Consolidated Sustainability Matrix (CSM) that integrates 189 sustainability indicators drawn from 25 certifications and 26 standards. The indicators are organized into 15 categories and mapped against BIM and DT capabilities to evaluate their operational potential across environmental, social, and economic dimensions.

The research is guided by two objectives.

1. To provide a comprehensive characterization of sustainability through the lens of standards and certifications and frame its operationalization in the built asset industry.
2. To evaluate the potential of digitalization, through BIM and DT capabilities, to enable this operationalization.

This study makes three contributions to the literature. First, it develops the CSM, a harmonized framework that integrates 189 indicators from certifications and standards into 15 categories. Second, it introduces two complementary metrics, the Cumulative Weighted Score (CWS) and the Weighted Agreement Score (WAS), to strengthen reliability and assess consensus in evaluating digital capabilities. Third, it provides mappings of both BIM and DT capabilities to sustainability indicators, thereby extending the discussion beyond fragmented applications toward a more holistic digitalization of sustainability.

The remainder of this paper is structured as follows. Section 2 presents the literature review, Section 3 presents the four-phases methodology, including CSM development, BIM/DT capabilities mapping, and operational evaluation. Section 4 reports the results, detailing the identified certifications and standards, the construction of the CSM, BIM and DT capabilities, and the results of the evaluation stage. Section 5 discusses the findings in light of existing literature and highlights the implications for industry and policy. Section 6 concludes by summarizing contributions, outlining limitations, and proposing directions for future research.

2. Literature review

Sustainability has long been recognized as a critical challenge in the built asset industry due to its significant contribution to climate change, resource consumption [2], and waste generation [20]. Since the Brundtland Commission's definition of sustainable development in 1987 [21], sustainability in construction has evolved from conceptual discussions toward structured assessment frameworks and performance standards. Building sustainability today is understood as a multidimensional concern, spanning environmental, economic, and social-cultural domains, and requiring measurable criteria for evaluation [5].

To operationalize these principles, a variety of sustainability certifications and standards have emerged. Certifications such as LEED (Leadership in Energy and Environmental Design) [22], BREEAM (Building Research Establishment Environmental Assessment Method) [23], Green Star [24], and DGNB (German Sustainable Building Council) [25] provide performance-based frameworks that incentivize sustainability through credit-based assessments [26], typically focusing on energy, emissions, water, and indoor environmental quality [27]. Complementary standards, including ISO 14001 [28], ISO 21930 [29], EN 15978 [30], ISO 26000 [31], and the Global Reporting Initiative (GRI) [32–35], provide methodological consistency for performance evaluation [36]. However, the coexistence of multiple frameworks generates complexity in implementation [7]. In practice, attention often narrows to environmental metrics such as energy modeling or carbon foot printing, while social and economic indicators remain underrepresented [8].

Digital technologies have been proposed as a means to overcome these challenges. BIM offers a collaborative digital environment for data management and analysis across the asset lifecycle [37]. Its role in sustainability, often referred to as "6D BIM" [10,11], supports integration with lifecycle assessment [38], energy analysis [16], and certification compliance [39]. Despite these benefits, BIM is inherently static and limited in responding to real-time operational changes [12].

DTs extend BIM by enabling dynamic, data-driven representations of physical assets that integrate IoT and sensor data [13]. DT applications have demonstrated potential for energy optimization [14], predictive maintenance [40], indoor air quality monitoring [18], water resource management [41], and renewable energy integration [42]. These capabilities position DTs as powerful tools for continuous performance evaluation and adaptive sustainability management [13,43].

Despite these advances, existing research is fragmented. Studies tend to examine individual capabilities, such as BIM for energy simulation [16], emissions tracking [17], lifecycle assessment [44], or waste management [45], without assessing their collective potential. Some works have mapped BIM functionalities to selected certification schemes [46], but their coverage is narrow and reveals gaps, particularly in addressing social and economic sustainability [47]. Standards remain largely absent from this discourse, and DT research is still limited to technical case studies. These gaps underscore the need for a consolidated framework that integrates indicators across certifications and standards and systematically evaluates the combined potential of BIM and DT to operationalize sustainability across environmental, social, and economic dimensions.

3. Methodology

The objective of the study presented in this paper is to evaluate the potential of digitalization, through BIM and DT capabilities, to operationalize sustainability, as characterized through the lens of standards and certifications. The methodology was therefore designed to address two overarching research objectives: (1) to provide a comprehensive characterization of sustainability through the lens of standards and certifications and frame its operationalization in the built asset industry, and (2) to evaluate the potential of digitalization, through BIM and DT capabilities, to enable this operationalization.

In doing so, this study examines the breadth of sustainability within the built asset industry by identifying and consolidating sustainability indicators from recognized certification schemes and standards. It also investigates the capabilities and applications of BIM and DT in addressing this broad spectrum of sustainability indicators, considering how and to what extent these technologies can enable their operationalization. To address these objectives, a four-phase methodology was developed (Fig. 1): Selection of certification and standards (phase 1); Consolidation of sustainability indicators through the five-step CSM development process (phase 2); Mapping of BIM and DT capabilities to the consolidated indicators (phase 3); and Evaluation of BIM/DT operational potential through workshops, surveys, and expert interviews (phase 4). Each of these phases is described in detail in the following sections.

3.1. Phase 1: selection of certification and standards

The selection of building certifications and standards began with a preliminary compilation of widely recognized schemes through desk-top research. This initial step utilized existing knowledge, industry reports, and scholarly articles to identify influential certifications such as LEED, BREEAM, and DGNB, alongside standards like ISO 14001 and the Global Reporting Initiative (GRI) series.

To refine and expand this list, a systematic review [48] was conducted across prominent online databases, including Scopus, and Web of Science. The search employed a combination of keywords such as "Sustainability", "Green Building Certifications", "GBRS (Green Building Rating System)", "LEED", "BREEAM", "Environmental Assessment Methods", "Eco-friendly Building Practices", and "Sustainability Standards" to ensure a targeted exploration of relevant certifications and standards.

The dataset was further expanded using the snowballing method [49], which involved reviewing references from initial sources to uncover additional relevant certifications and standards. Expert consultations were also used to enrich the list of certifications and standards. These took place through presentations to a group of university researchers, including two faculty members in the construction field.

To manage the resulting dataset, a database was created for all selected schemes and standards. This database recorded key attributes, including.

- Name and origin (country) of the certification or standard
- Year of establishment and most recent update
- Categories/sectors/areas (e.g., energy, water, materials)
- Weight of each category, if applicable
- Indicators, sub-criteria, or credits within each category
- Scope, grading systems, and reference sources

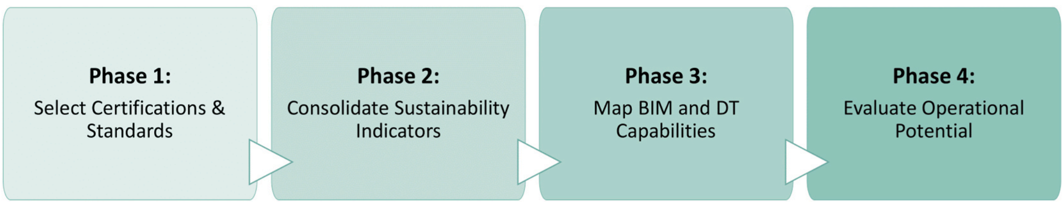

Fig. 1. Four-phased methodology.

These attributes ensured consistent documentation and enabled later consolidation and analysis. In total, 25 certifications and 26 standards were selected, forming the basis for the development of the CSM undertaken in Phase 2.

3.2. Phase 2: consolidation of sustainability indicators

The consolidation process transformed the raw indicator dataset compiled in Phase 1 into the CSM, a harmonized set of sustainability indicators suitable for more detailed analysis. The CSM was developed through five sequential steps as demonstrated in Fig. 2.

Step 1: Comparative Analysis and Harmonization of Indicators

Indicators from the 25 certifications and 26 standards were compared based on their definitions, measurement methods, tools, and scopes. Similar indicators were merged under harmonized descriptions, while methodological or scope differences were documented to maintain contextual integrity. This harmonization ensured that the final CSM preserved the intent of each original indicator while enabling a consistent interpretation across all sources. Rationalization of the indicators was supported through continuous dialogue within the research team, where harmonization actions for given indicators were debated prior to a final decision being made.

For example, the indicator “Reduction of Greenhouse Gas Emissions” was harmonized by synthesizing elements from multiple schemes: one emphasizing operational emissions reductions (e.g., energy efficiency and renewable integration), another addressing lifecycle emissions including construction, and others highlighting broader greenhouse gas coverage and strategies such as carbon offsets. The resulting unified description captured both operational and embodied phases, included multiple greenhouse gases, and allowed flexibility for emerging practices. A detailed account of this example is provided in the Results section (Section 4.2.1).

Step 2: Development of Preliminary Tables

Separate tables for certifications and standards were created based on the comparative analysis, ensuring they captured the range of identified indicators and categories. The certification table included 181 indicators, while the standards table comprised 227 indicators.

Step 3: Integration of Tables

Following the development of separate certification and standards tables, a second level of harmonization was carried out to integrate the two datasets into a unified structure. This process involved identifying overlaps between certification-derived indicators and standard-derived indicators, consolidating them into single descriptions, and retaining indicators that were unique to either set. Where definitions or scopes conflicted, the discrepancies were resolved through discussions and consensus-building. Uncertainties were addressed by consulting with colleagues in the research lab, whose input helped refine ambiguous cases. As with the first step, decisions to integrate certain indicators were debated within the research team to achieve consensus around a final indicator and meaning.

Step 4: Iterative Refinement

The unified table underwent iterative refinement through a presentation to a group of industry professionals affiliated with the university, complemented by feedback from a focus group comprised of members of the research lab to which the research team is affiliated. During these sessions, participants reviewed the sustainability indicators and provided insights that led to refinements in the matrix, including clarifications to indicator descriptions and suggestions for merging or separating specific entries.

Step 5: CSM Finalization and Documentation

The refined CSM comprised 189 sustainability indicators organized into 15 categories. A full methodological record was prepared to ensure transparency, traceability, and adaptability for future updates in response to evolving sustainability practices.

Fig. 2. Five-step process for developing the CSM.

3.3. Phase 3: mapping of BIM and DT capabilities to sustainability indicators

The mapping process began with a high-level evaluation of correspondence of BIM and DT capabilities to the sustainability categories developed within the CSM. This mapping aimed to identify relevant case studies and research projects that showcased the potential applications of BIM and DT to operationalize the indicators defined within the CSM. The mapping was informed by a literature review, which highlighted how BIM and DT can support efforts in areas such as Energy, Emissions, Waste, etc.

To refine this mapping, targeted searches were conducted using keywords derived from the indicators falling within each sustainability category. Keywords such as “Energy Simulation,” “Waste to Energy,” “Renewable Energy,” “Emissions Tracking,” “GHG,” “Construction Waste,” “Indoor Air Quality,” “Lifecycle Assessment,” “Biodiversity,” and “Brownfield Rehabilitation” were used in combination with Boolean search strings (AND BIM OR “Digital Twin”). These searches, carried out across databases such as Scopus, Engineering Village, and Google Scholar, allowed for the identification of studies that specifically focus on the integration of BIM and DT technologies in sustainability-related applications.

3.4. Phase 4: evaluation of operational potential

The final phase served to evaluate the operational potential of BIM and DT capabilities within the built asset industry. This evaluation employed a mixed-methods approach, combining qualitative and quantitative methods [50] to assess the practical implications of the framework. Digitalization capabilities were identified using a five-point scale developed in Poirier and Motamedi [51], positioning digital capabilities relating to BIM and DT on a continuous scale, going from No BIM or DT use to the deployment of a full digital twin. Each point on the scale is described in Table 1 and illustrated in Fig. 3.

3.4.1. Workshops

As part of the evaluation process, a workshop was conducted involving 18 graduate students (master’s and Ph.D.) with expertise in BIM, DT, and sustainable development. The workshop had a dual purpose: (i) to validate and refine the CSM, and (ii) to test the applicability of the five-point scale for evaluating BIM/DT capabilities. Participants were divided into three groups, each provided with structured evaluation charts to rate the applicability of BIM/DT integration levels for each sustainability indicator according to the predefined scale mentioned above. Quantitative data were collected directly from these evaluation charts, completed by participants during the session. Concurrently, qualitative data was gathered through observational notes documenting discussions, suggestions, and clarifications made by participants. This combined input informed refinements to the indicator set, including clarifications to descriptions, the consolidation of overlapping items, and adjustments to ensure consistency with BIM/DT applications. These refinements supported the finalization of the CSM and confirmed the suitability of the five-point scale for use in the subsequent survey and expert interview stages.

3.4.2. Surveys

Upon validation of the scoring approach, the research progressed to a broader survey stage to capture a wider range of perspectives on the applicability of BIM/DT in operationalizing the sustainability indicators within the CSM. The survey was distributed through various networks including industry newsletters, forums, social media, and directly to professionals to collect opinions in different domains including sustainable construction, BIM and DT.

The survey was structured into three main sections: (i) an introduction outlining the objectives, (ii) demographic questions, and (iii) the main assessment section, where participants selected relevant categories based on their expertise and interest. Each category contained 5 to 20 indicators, each with its own description, to guide participant evaluation. A five-point scale (Table 1) was used to assess BIM/DT integration, ranging from no BIM use to full Digital Twin implementation. An additional option was provided to allow participants to indicate if they considered an item to not be a valid sustainability indicator. Participants could also provide qualitative comments for additional insights.

A total of 41 responses were collected. The data was organized in Excel and imported into R Studio for analysis. To ensure that results reflected the expertise of respondents, demographic factors such as years of experience, level of BIM expertise, and familiarity with sustainability were used to assign weights to each response. This weighting approach [52], aimed to amplify the influence of more experienced respondents while retaining input from less experienced participants.

Weights were assigned on a scale from 1 to 6 for years of experience, and from 1 to 5 for both BIM expertise and sustainability familiarity. For each response, the three demographic weights were summed to produce a cumulative weight Wi. The overall CWS for

Table 1
Description of five-point scale for evaluating BIM/DT capabilities (adapted from Poirier & Motamedi (2024)).

No	Options	Description
0	No BIM Use	There is no incorporation of BIM methodologies.
1	Updated Digital Model	Utilization of BIM for periodic updates to digital models.
2	Shared Model	BIM facilitates sharing digital models for enhanced stakeholder collaboration.
3	Shared Model with Integrated Sensor Data	BIM integrates with sensor data, enriching the digital model’s utility and performance tracking.
4	Full Digital Twin	A comprehensive digital counterpart of the physical structure, dynamically updated with real-time data for in-depth analysis and optimization.

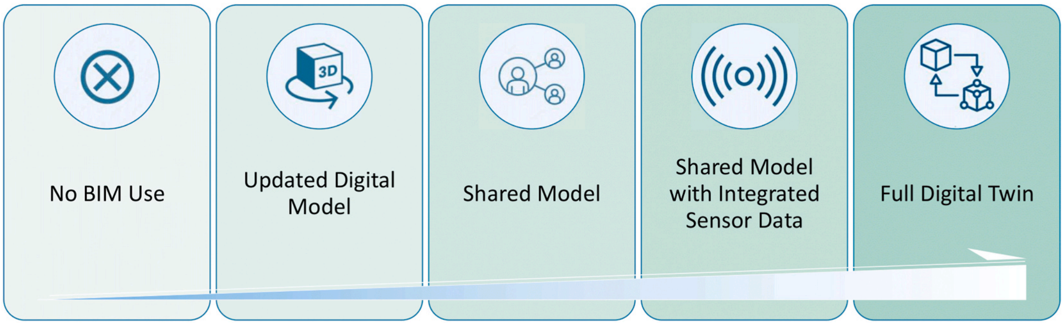

Fig. 3. Five-point scale for evaluating BIM/DT Capabilities (adapted from Poirier & Motamedi (2024)).

each option was then calculated as follows.

Equation (1): CWS Formula

$$CWS_j = \sum_{i=1}^{n} R_{ij} \times \mathrm{W}_i$$

Where:

CWS_j: cumulative weighted score for indicator option j

$\boldsymbol{R_{ij}}$: response of participant *i* for indicator j (1 if selected, 0 otherwise).

$\mathbf{W}_i$: weight assigned to participant *i* based on demographics

$\boldsymbol{n}$: Total number of respondents

For instant, for the "Forced or compulsory labor" indicator, the option "No BIM Use" received a high score because it was selected by several respondents with significant experience in both BIM and sustainability, which amplified its weighted total.

While low, the sample provided sufficient evidence to suit the exploratory nature of the research project aimed at uncovering trends in perceptions around sustainability indicators most suitable to be operationalized through digitalization. These findings were later confirmed through expert interviews.

3.4.3. Expert interviews

Semi-structured interviews [53] with three industry experts provided in-depth insights into the integration of BIM and DT within sustainability practices. Experts were selected from the authors' professional networks based on their demonstrated knowledge and experience in BIM, DT, and sustainability to ensure relevant and diverse perspectives. Interviews were conducted online, recorded, and transcribed for analysis. Discussions focused on evaluating sustainability indicators, BIM and DT capabilities, and survey results. Quantitative analysis was performed to assess the consistency of evaluations across interviewees.

3.4.4. Consensus analysis on sustainability indicators

Following the survey stages, a Weighted Agreement Score (WAS) was applied to assess the level of consensus amongst participants regarding the potential of BIM and DT to operationalize sustainability indicators. The objective was to identify which indicators have the highest agreement in terms of BIM and DT potential, and which require more detailed evaluation due to lower consensus.

This score is inspired by Fleiss's Kappa [54], a well-established statistical method for measuring agreement among multiple raters (survey respondents) on categorical items. However, instead of treating all respondents equally, our method introduces a weighted adaptation where respondent expertise (i.e., experience, BIM expertise, sustainability knowledge) informs the weight assigned to each individual response. This approach balances response popularity with participant credibility, allowing for a more nuanced and representative understanding of consensus. The WAS is calculated as follows:

Equation (2): WAS Formula

$$S_w = \frac{\sum_{i=1}^{n} (A_i \times \mathrm{W}_i)}{\sum_{i=1}^{n} W_i}$$

Where:

$\boldsymbol{S_w}$: Weighted Agreement Score

$\boldsymbol{A_i}$: Agreement value (1 if the response matches the most common answer, 0 otherwise).

$\mathbf{W}_i$: Weight assigned to participant *i* based on demographics

$\boldsymbol{n}$: Total number of respondents

This method ensures that the final score reflects both the consensus among respondents and the expertise of individuals, allowing for a more reliable understanding of the integration potential of BIM and DT for each sustainability indicator.

3.5. Bias mitigation

Measures to mitigate bias were implemented across all evaluation activities. These measures touched on survey design and question construction, sampling and recruitment, and analysis and interpretation. Regarding survey design and question construction, the survey was constructed and tested on a small sample in an iterative fashion. Every category and indicator were defined and explained within the survey to reduce interpretation. Moreover, participants chose which category they were most comfortable responding to at the onset of the survey. For instance, a respondent could choose to respond for a single category of indicators (e.g. emissions) and not respond for the other 14, based on their expertise. A Likert scale was used, as described above, whereby respondents were allowed to indicate that a certain indicator was not applicable. The survey was accessible online across several platforms.

Regarding sampling and recruitment, efforts were made to diversify the research sample by multiplying recruitment channels and approaches. For the workshop, participants brought expertise from diverse domains, including BIM, Digital Twin, and sustainability in construction. For the survey, respondents represented multiple geographic regions (North America, South America, Europe, and Asia) and came from varied professional backgrounds such as BIM management or coordination, architecture or engineering, project management, or others. They also varied in years of professional experience, company types, and levels of expertise in BIM and sustainability. For the expert interviews, the three selected experts represented different geographic regions and brought combined academic and professional experience in BIM, DT, and sustainability.

Finally, regarding analysis and interpretation, the use of the Weighted Agreement Score incorporated participants' self-reported expertise in each indicator category, ensuring that evaluations reflected balanced, informed perspectives without dominance from any single group.

4. Results

4.1. Phase 1: results of selecting sustainability certifications and standards

As previously explained, a total of 25 building certifications and 26 standards were identified through the systematic review. Tables 2 and 3 illustrate the selected certifications and standards, along with their geographic scopes, domains, and applicable scales. These 51 resources constituted the basis for the work on developing a harmonized view of sustainability for the built asset industry.

4.2. Phase 2: results of Consolidating Sustainability Indicators (CSM development)

The motivation behind the development of the CSM was the need to create a harmonized framework to streamline the assessment of digital capabilities across sustainability indicators. The CSM was created by integrating tables of indicators found within certifications and standards into a single cohesive structure. The process was used to harmonize overlapping indicators while retaining unique ones, resulting in a consolidated matrix, as shown in Fig. 4. The final CSM is comprised of a total of 189 indicators categorized into 15 sustainability categories. The full list of categories and their respective indicators are described in Table 4.

Table 2
List of selected building sustainability certification schemes.

No	Certification Name	Geographic Scope	Domain	Scale
1	BCA Green Mark [55]	Singapore	Building design, construction, and operation	Asset
2	BNB [56]	Germany	Building design, construction, and operation	Asset
3	BREEAM [23]	UK	Building design, construction, and operation	Asset
4	CASBEE [57]	Japan	Building design, construction, and operation	Asset
5	DGNB [25]	Germany	Building design, construction, and operation	Asset
6	E.E.W.H [58].	Taiwan	Building design, construction, and operation	Asset
7	ENVISION [59]	USA	Infrastructure Development	Asset
8	GBC HB [60]	Italy	Renovation and use of historic buildings	Asset
9	Green Globes [61]	Canada/USA	Building design, construction, and operation	Asset
10	Green Star [24]	Australia/NZ	Building design, construction, and operation	Asset
11	GRIHA [62]	India	Building design, construction, and operation	Asset
12	HK BEAM [63]	Hong Kong	Building design, construction, and operation	Asset
13	IGBC [64]	India	Building design, construction, and operation	Asset
14	ITACA [65]	Italy	Building design, construction, and operation	Asset
15	Klimaaktiv [66]	Austria	Building design, construction, and operation	Asset
16	LEED [22]	USA	Building design, construction, and operation	Asset
17	LEVEL(S) [67]	EU	Building design, construction, and operation	Asset
18	Lider A [68]	Portugal	Building design, construction, and operation	Asset
19	MINERGIE [69]	Swiss	Energy Efficiency in Buildings	Asset
20	MINERGIE-ECO [69]	Swiss	Energy Efficiency in Buildings	Asset
21	NABERS [70]	Australia	Energy Efficiency in Buildings	Asset
22	OGNB [71]	Austria	Building design, construction, and operation	Asset
23	One Planet [72]	Australia	Building design, construction, and operation	Organization
24	Passive House [73]	Germany	Energy Efficiency in Buildings	Asset
25	WELL [74]	USA	Health and Wellness in the Built Environment	Asset

Table 3
List of selected standards.

No	Standards Name	Geographic Scope	Domain	Scale
1	ASHRAE 189.1 [75]	USA	Building design, construction, and operation	Asset
2	CEN - EN 15804 [76]	Europe	Environmental Assessment of Construction Products	Asset
3	CEN - EN 15978 [30]	Europe	Built Environment Sustainability	Asset
4	GRI 200 Series [32]	Global	Economic performance Reporting	Organization
5	GRI 300 Series [33]	Global	Environmental impact Reporting	Organization
6	GRI 400 Series [34]	Global	Social impact Reporting	Organization
7	GRI Sector Series [35]	Global	Sector-Specific Sustainability Reporting	Organization
8	ISO 14001 [28]	Global	Environmental Management	Organization
9	ISO 14040 [77]	Global	Life Cycle Assessment (LCA)	Asset
10	ISO 14044 [78]	Global	Life Cycle Assessment (LCA)	Asset
11	ISO 14090 [79]	Global	Climate change adaptation in an organization	Organization
12	ISO 15392 [80]	Global	Building construction	Asset
13	ISO 20887 [81]	Global	Buildings and civil engineering works	Asset
14	ISO 21929 [82]	Global	Building construction	Asset
15	ISO 21930 [29]	Global	Environmental Assessment of Construction Products	Asset
16	ISO 26000 [31]	Global	Social Responsibility in Organizations	Organization
17	ISO 37101 [83]	Global	Sustainable Development in Communities	Organization
18	ISO 37120 [84]	Global	Sustainable Development in Communities	Organization
19	ISO 45001 [85]	Global	Occupational Health and Safety	Organization
20	LBC 4.0 [86]	USA	Building design, construction, and operation	Asset
21	PIEVC [87]	Canada	Climate Change in Public Infrastructure	Asset
22	SASB (Construction Materials) [88]	Global	Sustainability reporting in construction materials industry	Organization
23	SASB (Engineering Services) [89]	Global	Sustainability reporting in engineering services industry	Organization
24	SASB (Products and Furnishings) [90]	Global	Sustainability reporting in products and furnishings industry	Organization
25	SASB (Real Estate) [91]	Global	Sustainability reporting in real estate industry	Organization
26	SASB (Waste Management) [92]	Global	Sustainability reporting in waste management industry	Organization

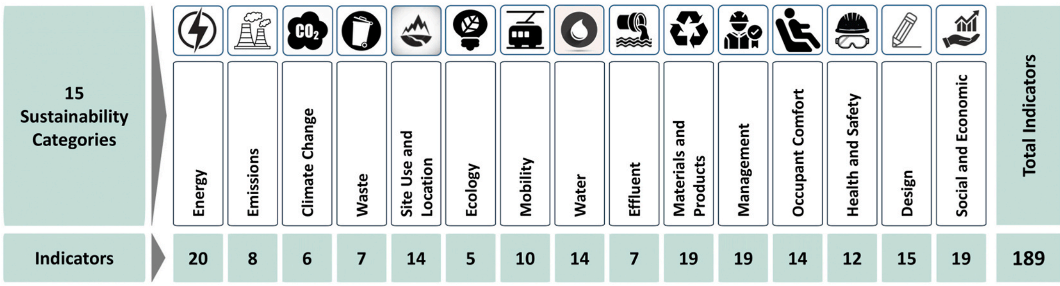

Fig. 4. CSM's categories and their related indicators.

4.2.1. Harmonization: example of the reduction of greenhouse gas emissions

The process of harmonization in the CSM involved synthesizing overlapping and complementary elements from various certification schemes and standards. This ensured each indicator captured the unique contributions of its sources while aligning with a comprehensive and actionable perspective on sustainability. The goal was to balance specificity with practicality, making the indicators adaptable to diverse contexts.

One example of this process is the Reduction of Greenhouse Gas Emissions indicator, selected because it was the most frequently recurring indicator across the dataset, appearing in 37 out of the 51 certifications and standards analyzed. The terminology used for this indicator is not directly adopted from a single certification but is instead a harmonized term derived from multiple schemes. While different standards address greenhouse gas (GHG) emissions through varying scopes and terminologies, such as "operational emissions reduction" (LEED) [22], "lifecycle emissions reduction" (Envision) [59], and "net-positive carbon" (LBC) [86], this study aligned them under a unified definition that captures both operational and embodied carbon impacts.

To achieve this harmonization, the descriptions, scopes, and evaluation methods of related indicators were compared across multiple schemes, rather than relying solely on indicator names. This comparison was conducted through a coding process [93], where each indicator's definition, assessment criteria, and sustainability focus were classified into common themes. The five certifications used in this example illustrate how different sustainability frameworks approach GHG reduction.

- LEED focuses on operational emissions reduction via energy efficiency, grid harmonization, and renewable energy integration [22].
- Envision incorporates lifecycle emissions strategies, including carbon offsets and sequestration [59].
- BNB emphasizes precise calculations of emissions during building operations [56].
- GRI Standards highlight standardized reporting for various greenhouse gases, including methane and nitrous oxide [33].

Table 4
CSM's categories and indicators.

No	Code	**Cat 01 - Energy**
1	EN01	Primary energy demand
2	EN02	Flexible demand side response
3	EN03	Energy efficiency/performance
4	EN04	Energy monitoring
5	EN05	Energy metering
6	EN06	Heat requirement/Insulation
7	EN07	Consumption forecast
8	EN08	Building shell airtight/Thermal bridge
9	EN09	Renewable energy
10	EN10	Enhanced Commissioning
11	EN11	Grid harmonization
12	EN12	Energy conservation/Reduction
13	EN13	Tenancy sub-metering
14	EN14	Power density/Energy intensity
15	EN15	Decentralized energy consumption
16	EN16	Non-renewable alternative Sources
17	EN17	Fleet fuel management
18	EN18	Landfill Gas to Energy
19	EN19	Materials for Energy recovery
20	EN20	Exported Energy
No	Code	**Cat 02 - Emissions**
21	EM01	NOx/SOx emissions
22	EM02	Particulate matter
23	EM03	Volatile organic compounds (VOCs)
24	EM04	Polycyclic aromatic hydrocarbons (PAHs)
25	EM05	Hazardous air pollutants (HAPs)
26	EM06	Ventilation
27	EM07	Indoor air quality
28	EM08	Waste facilities near dense population area
No	Code	**Cat 03 - Climate Change**
29	CL01	Reduction of Greenhouse Gas Emission
30	CL02	Photochemical Ozone creation potential
31	CL03	Ozone Depletion Potential (ODP)
32	CL04	Acidification for soil and water
33	CL05	Eutrophication
34	CL06	Depletion of abiotic resources
No	Code	**Cat 04 - Wastes**
35	WS01	Construction waste management
36	WS02	Demolition waste management
37	WS03	Organic waste treatment
38	WS04	Recycled Wastes management
39	WS05	Waste incinerated measurement
40	WS06	Waste to energy materials
41	WS07	Transport of hazardous waste
No	Code	**Cat 05 - Site Use and Location**
42	LU01	Site selection
43	LU02	Construction pollution prevention
44	LU03	Site assessment
45	LU04	Site plan
46	LU05	Landscape/Greenery
47	LU06	Heat island reduction
48	LU07	Light pollution reduction
49	LU08	Farmland protection
50	LU09	Soil protection
51	LU10	Reclaim Brownfield/Contaminated land
52	LU11	Risk of the location/Hazards
53	LU12	Image/Influence of location
54	LU13	Near to amenities
55	LU14	Site development
No	Code	**Cat 06 - Ecology**
56	EC01	Site Ecology improvement
57	EC02	Biodiversity enhancement/preservation
58	EC03	Terrestrial acreage disturbed
59	EC04	Operational sites in or near protected area
60	EC05	Habitats protected or restored
No	Code	**Cat 07 - Mobility**
61	MB01	Public transport accessibility
62	MB02	Car parking capacity
63	MB03	Car Share policy
93	MT02	Responsible sourcing of materials
94	MT03	Design for durability
95	MT04	Design for flexibility
96	MT05	Material efficiency
97	MT06	Material resiliency
98	MT07	Resource extraction/Regional material
99	MT08	Easy cleaning
100	MT09	Easy recycling
101	MT10	Exclusion of harmful substances
102	MT11	Environmental Product Declaration (EPD)
103	MT12	Use of green product/Low-emitting product
104	MT13	Utilizing alternative materials
105	MT14	Prefabrication
106	MT15	Sustainable forest materials/Wood
107	MT16	Traceability
108	MT17	Reused Materials
109	MT18	Recycled Materials
110	MT19	Product risk assessment
No	Code	**Cat 11 - Management**
111	MG01	Life cycle costs
112	MG02	Project plan
113	MG03	Service life planning
114	MG04	Responsible construction practice
115	MG05	Building Commissioning
116	MG06	Aftercare
117	MG07	Handover
118	MG08	Contract awarding/tendering phase
119	MG09	Documentation
120	MG10	Effective leadership and commitment
121	MG11	Teamwork and collaboration
122	MG12	Stakeholder involvement
123	MG13	Plan for end of life
124	MG14	Building user's guide/Training
125	MG15	metering and monitoring/Digital facility management
126	MG16	Risk management
127	MG17	Scheduled maintenance plan
128	MG18	Quality assurance
129	MG19	Property investment analysis
No	Code	**Cat 12 - Occupant Comfort**
130	OC01	Visual comfort
131	OC02	Thermal comfort
132	OC03	Acoustic Comfort
133	OC04	Olfactory comfort
134	OC05	Private space
135	OC06	Security of the Building
136	OC07	Quality of use
137	OC08	Influence of the user/Interface Technologies
138	OC09	Tobacco smoke control
139	OC10	Air monitoring and management
140	OC11	Quality of life improvement
141	OC12	Regional/Local priority
142	OC13	Access to Nature
143	OC14	furnishing
No	Code	**Cat 13 - Occupant health and Safety**
144	HS01	Total recordable incident rate
145	HS02	Fatality rate
146	HS03	Near miss frequency rate
147	HS04	Reported cases of Silicosis
148	HS05	Safe containment in laboratories
149	HS06	Management of Hazardous chemical
150	HS07	Safety Measurement System for driving
151	HS08	Road accidents measurement
152	HS09	Ionizing radiation
153	HS10	Worker participation on occupational health and safety
154	HS11	Worker training on occupational health and safety
155	HS12	Public health and safety improvement
No	Code	**Cat 14 - Design**
156	DS01	Space efficiency
157	DS02	Project Design Strategies
158	DS03	Functionality

(*continued on next page*)

Table 4 (*continued*)

64	MB04	Small car space	159	DS04	Adaptability
65	MB05	Travel plan	160	DS05	Disassembly
66	MB06	Green mobility/transportation	161	DS06	Hazard Resistant/Resiliency
67	MB07	Bicycle traffic	162	DS07	Structure/Floor load rating
68	MB08	Pedestrian oriented	163	DS08	Joint use of facilities
69	MB09	Development with Transportation Access	164	DS09	Fire safety
70	MB10	Construction impacts on Mobility	165	DS10	Inclusive Design
No	Code	**Cat 08 - Water**	166	DS11	Home office
71	WT01	Water consumption optimization	167	DS12	Wildland-urban interface design
72	WT02	Water withdrawal	168	DS13	Preserve historic and cultural resources
73	WT03	Water monitoring/Metering	169	DS14	Enhance public spaces and amenities
74	WT04	Water leak detection	170	DS15	Urban planning and design
75	WT05	Water demand	No	Code	**Cat 15 - Social and Economic**
76	WT06	Irrigation system	171	SE01	Commercial viability
77	WT07	Water resource management	172	SE02	Universal Access/Equitable access
78	WT08	Water Treatment	173	SE03	Discrimination at work
79	WT09	Water quality	174	SE04	Human Rights policies
80	WT10	Water self-sufficiency	175	SE05	Community Engagement
81	WT11	Twin tank system	176	SE06	Arts and Culture Plan
82	WT12	Water intensive application	177	SE07	Upgrading employee skills (Education and Training)
83	WT13	Water contaminants	178	SE08	Fair Marketing and contractual practices
84	WT14	Water additives	179	SE09	Consumer data protection and privacy
No	Code	**Cat 09 - Effluent**	180	SE10	Access to essential services
85	EF01	Water discharge	181	SE11	Child Labor
86	EF02	Recycled/Reclaimed Water	182	SE12	Forced or compulsory labor
87	EF03	Rainwater/Stormwater	183	SE13	Direct economic value
88	EF04	Sewer system	184	SE14	Indirect economic impacts
89	EF05	landfill releases corrective actions	185	SE15	Financial assistance
90	EF06	Significant spills	186	SE16	Transparency
91	EF07	Water bodies affected by water discharges	187	SE17	Anti-corruption activities
No	Code	**Cat 10 - Materials and Products**	188	SE18	Tax related topics
92	MT01	Life cycle Assessment	189	SE19	Employment related topics

- LBC promotes net-positive carbon strategies like renewable energy generation and carbon sequestration [86].

The final harmonized indicator is defined as:

“Minimize or eliminate the release of gases contributing to climate change, such as carbon dioxide, methane, and nitrous oxide, through sustainable practices and technologies."

This harmonized definition ensures comprehensive coverage of emissions reduction across both operational and embodied phases of the building lifecycle while accommodating emerging practices like carbon offsets and net-positive carbon approaches.

4.3. Phase 3: results of mapping BIM and DT capabilities (digitalization of indicators)

The mapping of digital capabilities across the sustainability categories and indicators defined in the CSM reveals a wide range of potential applications for BIM and DT technologies in enhancing sustainability within the built environment. The results emphasize how BIM and DT contribute to various aspects of sustainability, such as energy efficiency, emissions reduction, waste optimization, and improved resource management.

Through a review of case studies, simulation-based studies, and quantitative analyses, the study identifies the alignment of BIM and DT functionalities with key sustainability indicators. For instance, BIM and DT are instrumental in supporting energy performance simulation, renewable energy management, real-time energy monitoring, and lifecycle energy analysis. Similarly, their application in emissions tracking, indoor air quality management, and ventilation system optimization demonstrates their potential to address environmental and health-related concerns in building design and operation.

The results also highlight specific examples of how BIM and DT have been implemented in practice. These include the use of BIM to optimize the building commissioning processes, integrating renewable energy systems into heritage buildings, and leveraging real-time digital twin models for energy consumption optimization and grid harmonization. Table 5 provides an overview of 54 digital capabilities to support operationalization of one or more sustainability indicators, mapped across the 15 sustainability categories, along with references derived from the literature review. As discussed, while Table 5 shows a considerable body of work related to operationalizing key sustainability indicators, most of these studies have addressed these indicators in isolation, thereby potentially missing the opportunities for digitalization to support achieving sustainability goals from a more holistic perspective.

4.4. Phase 4: results from the evaluation process

The evaluation process focused primarily on the results from the survey and expert interviews, which provided insights into the operational potential of BIM/DT for sustainability. These stages built on earlier workshop activities that helped validate the CSM and

Table 5
Examples of BIM and DT capabilities across sustainability categories.

Category	BIM and DT Capabilities	References
01- Energy	Energy Performance Simulation	[16]
	Renewable Energy Management	[94]
	Real-time Energy Monitoring	[95]
	Heat Load Analysis	[96]
	Demand Response Management	[97]
	Grid Interaction and Harmonization	[98]
	Energy Consumption Optimization	[99]
	Lifecycle Energy Analysis	[44]
	Enhanced Building Commissioning	[100]
	Energy Metering and Sub-metering	[40]
	Real-time Data Analysis for Energy Systems	[101]
02- Emissions	Emissions Tracking and Analysis	[102]
	Indoor Air Quality Simulation	[103]
	Ventilation System Optimization	[104]
	Air Quality Management	[17]
03- Climate Change	GHG Emissions Reduction Analysis	[105]
	Ecosystem Impact Modeling	[106]
04- Waste	Waste Stream Analysis	[107]
	Construction and Demolition Waste Management	[45]
	Waste to Energy System Modeling	[108]
05- Site Use and Location	Site Selection Analysis	[109]
	Heat Island Effect Reduction	[110]
	Brownfield Rehabilitation Planning	[111]
06- Ecology	Biodiversity Impact Assessment	[112]
	Ecological Value Mapping	[113]
07- Mobility	Accessibility Analysis	[114]
	Transportation System Integration	[115]
08- Water	Water Usage Optimization	[41]
	Water System Monitoring	[116]
	Leak Detection System Integration	[117]
	Water Treatment and Recycling Analysis	[118]
09- Effluent	Effluent Discharge Monitoring	[119]
	Stormwater Management Planning	[120]
10- Materials and Products	Lifecycle Assessment Integration	[39]
	Environmental Product Declaration (EPD) Management	[121]
	Prefabrication and Modular Construction Planning	[122]
	Sustainable Material Tracking	[123]
11- Management	Lifecycle Costing	[124]
	Digital Facility Management	[125]
	Risk Management and Safety Planning	[126]
	Quality Assurance Process Integration	[127]
	Maintenance Scheduling and Monitoring	[128]
12- Occupant Comfort	Comfort Parameter Simulation	[129]
	Environmental Quality Monitoring	[18]
	User Interaction and Interface Integration	[130]
13- Health and Safety	Safety Incident Tracking	[131]
	Occupational Health and Safety Training Integration	[132]
14- Design	Space Utilization Analysis	[133]
	Structural Resilience Simulation	[134]
	Universal Design Principles Application	[135]
	Historic Preservation Planning	[136]
15- Social and Economic	Community Engagement Facilitation	[137]
	Policy Compliance Monitoring	[138]
	Transparency and Anti-Corruption Modeling	[139]

confirm the usability of the scoring framework.

4.4.1. Survey results

4.4.1.1. Demographic information of survey respondents. The survey gathered responses from 41 professionals across various roles, including BIM managers, consultants, engineers, architects, and students. Table 6 presents the demographic distribution of respondents based on years of experience, company type, BIM expertise, job function, and familiarity with sustainability. Expertise in BIM was mixed, with an even split between beginners and experts, and most respondents were familiar with sustainability concepts.

4.4.1.2. Perspectives on the potential of digitalization to operationalize sustainability indicators. Fig. 5 illustrates the distribution of BIM/DT capability levels expressed as a percentage of total weighted responses. Percentages were calculated by normalizing the weighted

Table 6
Demographic breakdown of survey respondents (N = 41 participants).

Category	Sub-Category	Frequency (N)	Percentage (%)
Function in the organization	BIM Manager or BIM coordinator	5	12 %
	Consultant	4	10 %
	Engineer, Architect or other professional	12	29 %
	Other	3	7 %
	Project manager or coordinator	5	12 %
	Student	11	27 %
	Support (administration, accounting, etc.)	1	3 %
	Grand Total	41	100.00 %
Years of Experience	1–5 years	13	32 %
	11–20 years	9	22 %
	21–30 years	5	12 %
	6–10 years	8	20 %
	Less than 1 year	5	12 %
	More than 30 years	1	2 %
	Grand Total	41	100.00 %
Type of Company	Architecture	3	7 %
	Client/Owner-operator	7	17 %
	Engineering	10	24 %
	General contractor	1	3 %
	Other	19	46 %
	Specialty trade	1	3 %
	Grand Total	41	100.00 %
Location	Inside Canada	32	78 %
	Outside Canada	9	22 %
	Grand Total	41	100.00 %
Province	Ontario	1	2 %
	Quebec	31	76 %
	Other	9	22 %
	Grand Total	41	100.00 %
Level of BIM Expertise	None	8	19 %
	Beginner	12	29 %
	Intermediate	9	23 %
	Expert	12	29 %
	Grand Total	41	100.00 %
Familiarity with Sustainability	Not at all familiar	2	5 %
	Not very familiar	7	17 %
	Familiar enough	13	32 %
	Somewhat familiar	8	19 %
	Very familiar	11	27 %
	Grand Total	41	100.00 %

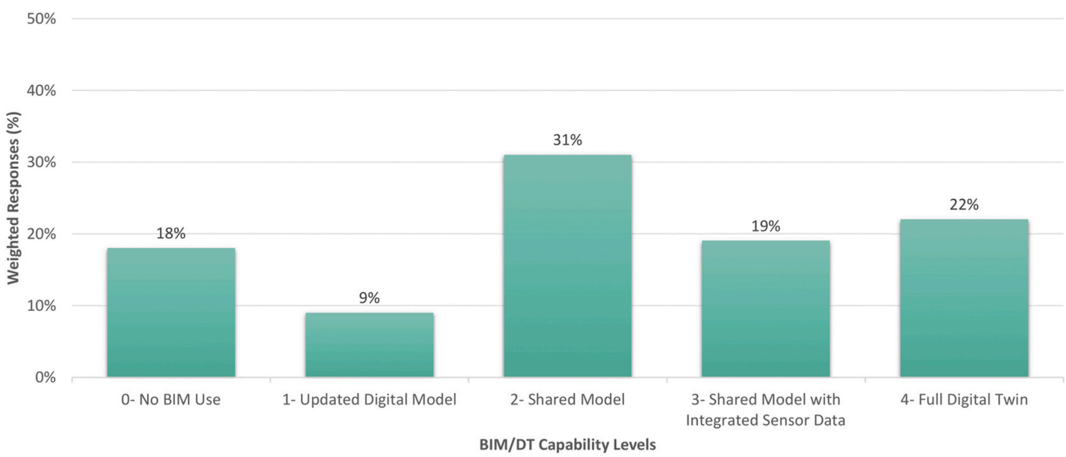

Fig. 5. Distribution of BIM/DT capability levels selected for sustainability indicators in the survey (N = 41 participants).

scores across all responses, where weights accounted for years of experience, BIM expertise, and familiarity with sustainability, as described in the Methodology section. As shown, participants identified "Shared Model" as the most widely applicable digital capability, with "Full Digital Twin" and "Shared Model with Integrated Sensor Data" also being highly ranked. This indicates a trend in perceptions toward more advanced digital capabilities to drive sustainability. On the other hand, 9 % of indicators were seen as operationalizable through “Updated Digital Models”, whereas 18 % of sustainability indicators were seen as not being operationalizable through any form of BIM or DT use.

4.4.1.3. Category-Wise Distribution of BIM/DT capability levels. More detailed analysis of BIM/DT capability levels across different sustainability categories revealed distinct trends as shown in Fig. 6. In the Energy and Emission categories, respondents strongly favored more advanced BIM integration, particularly Shared Models with Integrated Sensor Data and Full Digital Twins, highlighting the perceived value of real-time data and comprehensive digital modeling and simulation. Conversely, in the Social and Economic category, the majority selected No BIM Use, indicating limited relevance of BIM or DT in operationalizing these indicators. Categories such as Management, Design, and Materials and Products were viewed as suitable to be achieved through Shared Models, emphasizing BIM’s importance in collaboration and iterative project updates. For Occupant Comfort, Water, and Occupant Health and Safety, respondents notably leaned towards Full Digital Twin, reflecting recognition of the benefits of dynamic real-time digital capabilities. The numbers shown in each column represent the sum of the individual scores for the indicators within a category that were assigned a specific BIM/DT capability level by respondents (e.g., Social and Economic, which has 19 indicators, had a total of 132 selections for No BIM Use across all indicators, while Energy, with a total of 20 indicators, had 118 for Shared Model with Integrated Sensor Data across all indicators).

4.4.1.4. Ranking sustainability indicators by BIM/DT capability level. This section identifies the top sustainability indicators across the five BIM/DT capability levels. The prioritization is based on the survey results, where participants assigned weighted responses reflecting their expertise, professional background, and years of experience. The values reported in this section represent cumulative weighted totals, indicating the relative importance of each indicator at a given BIM/DT capability level. A higher total suggests stronger participant weighting toward that indicator, while lower totals suggest less emphasis or relevance (Table 7).

For No BIM Use, the highest-ranked indicators are Forced or compulsory labor, Car share policy, and Child labor. These emphasize ethical practices and basic mobility considerations, focusing on foundational social and equity concerns.

With the use of an Updated Digital Model, priorities shift to indicators such as small car space, Operational sites in or near protected areas, and near to amenities. These reflect attention to spatial efficiency, environmental conservation, and accessibility, laying the groundwork for sustainable project management, where static, mono-disciplinary information models are sufficient to support decision-making.

At the Shared Model level, where collaborative use of digital models occurs, the focus sharpens on Space efficiency, Project design strategies, and Urban planning and design. These indicators highlight the importance of optimizing design and planning to ensure long-term sustainability in urban and project contexts.

As projects integrate sensor data with a Shared Model, operational sustainability takes precedence, with key indicators being Energy metering, Indoor air quality, and Hazardous air pollutants (HAPs). These underscore the critical role of real-time monitoring in managing energy consumption and safeguarding environmental health both indoors and outdoors.

At the Full Digital Twin level, the leading indicators are Air monitoring and management, Energy conservation/reduction, and Building commissioning. These represent the potential of advanced technologies to deliver comprehensive sustainability through dynamic performance insights and proactive operational management.

Overall, the progression of priorities across digitalization levels reveals a shift from addressing ethical and basic spatial concerns in early stages to tackling intricate operational and environmental challenges at advanced stages. Notably, energy-related indicators

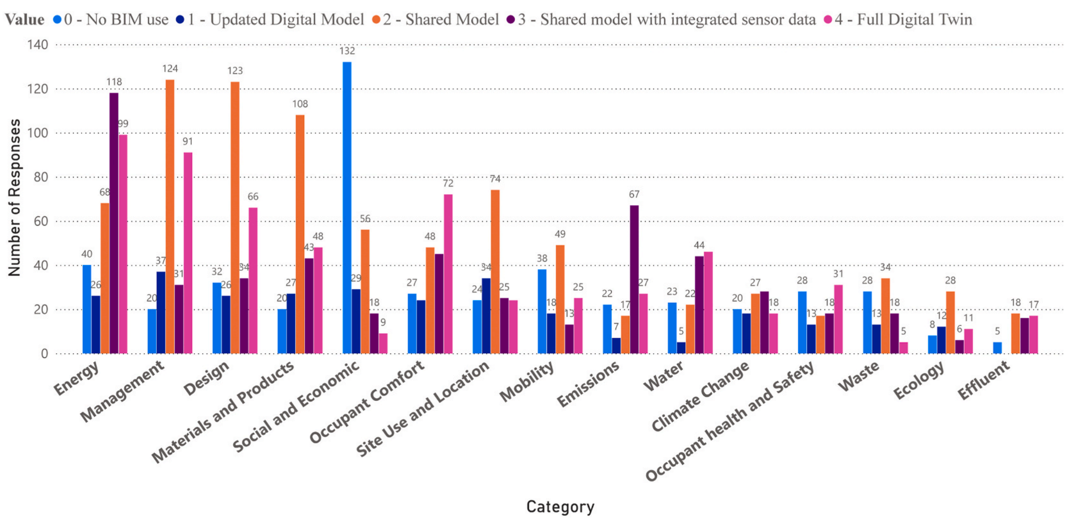

Fig. 6. Category-wise distribution of BIM/DT capability levels.

Table 7
Top sustainability indicators ranked for different BIM/DT capability levels.

BIM/DT Capability Level	Ranked Top 10 Indicators		CWS
No BIM Use	1.	Forced or compulsory labor	109
	2.	Car Share policy	101
	3.	Child Labor	100
	4.	Fleet fuel management	95
	5.	Employment related topics	94
	6.	Anti corruption activities	90
	7.	Discrimination at work	90
	8.	Human Rights policies	88
	9.	Financial assistance	84
	10.	Tax related topics	84
Updated Digital Model	1.	Small car space	51
	2.	Operational sites in or near protected area	48
	3.	Near to amenities	47
	4.	Access to Nature	46
	5.	Commercial viability	43
	6.	Ozone Depletion Potential (ODP)	43
	7.	Effective leadership and commitment	40
	8.	Private space	39
	9.	Habitats protected or restored	37
	10.	Image/Influence of location	37
Shared Model	1.	Space efficiency	121
	2.	Project Design Strategies	117
	3.	Urban planning and design	114
	4.	Functionality	113
	5.	Stakeholder involvement	111
	6.	Structure/Floor load rating	107
	7.	Demolition waste management	102
	8.	Heat requirement/Insulation	101
	9.	Construction pollution prevention	99
	10.	Project plan	99
Shared Model + Sensor Data	1.	Energy metering	111
	2.	Indoor air quality	103
	3.	Hazardous air pollutants (HAPs)	102
	4.	Tenancy sub-metering	98
	5.	Exported Energy	95
	6.	Particulate matter	95
	7.	NOx/SOx emissions	94
	8.	Ventilation	93
	9.	Volatile organic compounds (VOCs)	93
	10.	Energy monitoring	83
Full Digital Twin	1.	Air monitoring and management	106
	2.	Energy conservation/Reduction	92
	3.	Building Commissioning	87
	4.	metering and monitoring/Digital facility management	84
	5.	Aftercare	80
	6.	Property investment analysis	80
	7.	Quality of life improvement	76
	8.	Scheduled maintenance plan	75
	9.	Risk management	74
	10.	Consumption forecast	73

emerge prominently at higher BIM levels, underscoring digitalization to support energy efficiency as an important area of development. Additionally, the consistent inclusion of indicators such as Indoor air quality and Air monitoring and management reflects the growing emphasis on digitalization to support occupant well-being.

4.4.1.5. Consensus analysis on sustainability indicators. As part of the identification of overall trends in perceptions around the potential to develop digital capabilities to operationalize sustainability indicators, there was a need to understand if there was consensus on these rankings amongst participants. This was done to identify any indicators which might require more detailed evaluation in subsequent research phases due to lower consensus. Indeed, as shown below, while the survey results demonstrate overall trends and consensus in the participants perspective on digitalization to support operationalization of sustainability indicators, certain indicators did not achieve high-level of consensus.

The survey provided a quantitative measure of consensus through the Weighted Agreement Score. This metric reflects the level of agreement across respondents and incorporates the significance of their demographic attributes. A theoretical maximum possible consensus score is 1 (i.e., all 41 participants, across all response profiles, selecting the same option). As this is impossible to achieve, a relative ranking was used in this case to portray a nuanced reflection of the collective viewpoint, balancing the popularity of an indicator with the credibility of the opinion of a respondent. A consensus score of 0.25 and above was deemed high, whereas a score below 0.15 was deemed low given the distribution and profile of the sample.

As presented in Table 8, some indicators, such as 'Space efficiency' (DS 01) and 'Project Design Strategies' (DS 02), received high scores, indicating more consensus on their importance in BIM and DT applications. Conversely, indicators like 'Water resource management' (WT 07) and 'Rainwater/Stormwater management' (EF 03) scored lower, suggesting limited agreement among participants. Such low consensus likely results from differences in respondent background and perspectives on the topic. It could also result from differences in interpretation of the indicator's description, despite measures taken to mitigate this, lack of familiarity with its application, or limited expertise in using BIM/DT for these specific areas. For this reason, indicators with lower consensus were carried forward to the subsequent expert evaluation stage, where they were examined in greater depth to clarify definitions, explore relevant use cases, and assess their applicability with input from domain specialists.

4.4.2. Expert interview results

The collection of expert perspectives on digitalization to operationalize sustainability indicators yielded insightful data from the three industry experts. They discussed sustainability categorization, reacted to survey findings, and evaluated BIM and DT capabilities across some indicators, highlighting diverse opinions and perspectives (Table 9).

The interviews also provided quantitative data, revealing consensus levels among experts on BIM and DT capabilities for various indicators. Table 10 shows the highest agreement scores, with 19 out of 40 indicators that were discussed in the interviews receiving unanimous consensus, allowing to refine the overall tally. The expert interviews underscore the need for an integrated approach to sustainability that leverages BIM and DT capabilities, aligns with global standards, and addresses interconnected sustainability issues. The strong consensus on specific indicators suggests areas for focused research, development, and implementation to achieve transformative sustainability outcomes. This confirmation through expert interviews supported a final scoring of digitalization capabilities to operationalize sustainability indicators.

5. Discussion

This study examined how BIM and DT can help operationalize sustainability in the built asset industry using the CSM. The results highlight both the strengths of digitalization in addressing environmental sustainability and the persistent limitations in supporting social and economic dimensions.

5.1. Environmental sustainability

BIM and DT demonstrated their strongest contributions in categories such as energy, emissions, and indoor environmental quality. BIM's capabilities in energy modeling [16], life-cycle assessment [44], and certification alignment [140] confirm previous findings on its role in environmental performance analysis. DT extends these functions by enabling real-time monitoring [18], predictive analytics,

Table 8
Indicators with the Highest and Lowest Weighted Agreement Score, left: Highest, right: Lowest.

Indicators with highest consensus				Indicators with Lowest consensus			
Rank	**Code**	**Indicator Name**	**WAS**	**Rank**	**Code**	**Indicator Name**	**WAS**
1	DS 01	Space efficiency	0.32	165	WT 07	Water resource management	0.12
2	DS 02	Project Design Strategies	0.31	166	EF 03	Rainwater/Stormwater	0.12
3	DS 15	Urban planning and design	0.30	167	EC 01	Site Ecology improvement	0.11
4	DS 03	Functionality	0.30	168	SE 01	Commercial viability	0.11
5	EN 05	Energy metering	0.30	169	EM 08	Waste facilities near dense population area	0.11
6	MG 12	Stakeholder involvement	0.30	170	WT 13	Water contaminants	0.11
7	SE 12	Forced or compulsory labor	0.29	171	WT 02	Water withdrawal	0.11
8	DS 07	Structure/Floor load rating	0.28	172	EF 01	Water discharge	0.11
9	OC 10	Air monitoring and management	0.28	173	WT 08	Water Treatment	0.11
10	EM 07	Indoor air quality	0.27	174	LU 11	Risk of the location/Hazards	0.10
11	EM 05	Hazardous air pollutants (HAPs)	0.27	175	HS 04	Reported cases of Silicosis	0.10
12	WS 02	Demolition waste management	0.27	176	CL 02	Photochemical Ozone creation potential	0.10
13	EN 06	Heat requirement/Insulation	0.27	177	HS 02	Fatality rate	0.09
14	MB 03	Car Share policy	0.27	178	HS 03	Near miss frequency rate	0.09
15	SE 11	Child Labor	0.27	179	HS 05	Safe containment in laboratories	0.09
16	LU 02	Construction pollution prevention	0.26	180	HS 06	Management of Hazardous chemical	0.09
17	MG 02	Project plan	0.26	181	HS 10	Worker participation on occupational health and safety	0.09
18	EN 13	Tenancy sub-metering	0.26	182	HS 11	Worker training on occupational health and safety	0.09
19	DS 14	Enhance public spaces and amenities	0.26	183	WT 10	Water self-sufficiency	0.09
20	DS 06	Hazard Resistant/Resiliency	0.25	184	EF 02	Recycled/Reclaimed Water	0.09
21	EM 02	Particulate matter	0.25	185	WT 12	Water intensive application	0.09
22	EN 17	Fleet fuel management	0.25	186	EF 07	Water bodies affected by water discharges	0.09
23	EN 20	Exported Energy	0.25	187	HS 12	Public health and safety improvement	0.08
24	DS 05	Disassembly	0.25	188	HS 01	Total recordable incident rate	0.08
25	EM 01	NOx/SOx emissions	0.25	189	HS 09	Ionizing radiation	0.08

Table 9
Expert insights on BIM and DT integration in sustainability practice: Summary of perspectives.

Experts	Opinion on the 15 sustainability categories	Thoughts on the survey results alignment	Thoughts on the survey results alignment
Expert 1	Suggested more consolidated categorization.	Saw potential beyond current usage.	Highlighted BIM's role in managing environmental risks.
Expert 2	Emphasized interconnectedness without overlap.	Advocated for greater awareness among respondents.	Agreed on BIM's utility in environmental management.
Expert 3	Recommended aligning with global standards.	Indicated industry progress towards integrated use.	Noted BIM's role in asset management and DTs in optimization.

Table 10
Consensus on BIM/DT capabilities for sustainability indicators: Highest agreement scores (N = 3 experts).

No	Indicator Name	BIM/DT Capabilities	Agreement
1	Waste facilities near dense population area	2 - Shared Model	100 %
2	Near to amenities	2 - Shared Model	100 %
3	Site development	2 - Shared Model	100 %
4	Operational sites in or near protected area	2 - Shared Model	100 %
5	Water resource management	3 - Shared model with integrated sensor data	100 %
6	Water Treatment	3 - Shared model with integrated sensor data	100 %
7	Twin tank system	2 - Shared Model	100 %
8	Water contaminants	3 - Shared model with integrated sensor data	100 %
9	Water discharge	3 - Shared model with integrated sensor data	100 %
10	Recycled/Reclaimed Water	3 - Shared model with integrated sensor data	100 %
11	Rainwater/Stormwater	3 - Shared model with integrated sensor data	100 %
12	Significant spills	3 - Shared model with integrated sensor data	100 %
13	Water bodies affected by water discharges	3 - Shared model with integrated sensor data	100 %
14	Tobacco smoke control	4 - Full Digital Twin	100 %
15	Total recordable incident rate	2 - Shared Model	100 %
16	Reported cases of Silicosis	2 - Shared Model	100 %
17	Ionizing radiation	3 - Shared model with integrated sensor data	100 %
18	Commercial viability	2 - Shared Model	100 %
19	Direct economic value	2 - Shared Model	100 %

and adaptive system optimization [42], strengthening the operational dimension of sustainability. The survey results showed high agreement that advanced levels of digitalization -particularly shared models with integrated sensor data and full DT-are critical in these categories. This confirms that the integration of BIM and DT provides complementary value: BIM supports early-stage modeling, while DT ensures continuous performance management across the asset lifecycle.

5.2. Social sustainability

In contrast, indicators related to labor rights, inclusivity, occupant well-being, and community engagement received low ratings for BIM and DT applicability. While BIM offers some capacity for modeling occupant comfort and accessibility, and DT can enhance monitoring of indoor environmental quality [18], these contributions remain narrow compared to the breadth of social indicators in the CSM. Respondents also expressed weaker consensus in this domain, reflecting uncertainty and limited maturity in digital solutions for social sustainability. This gap mirrors critiques in the literature that sustainability assessments and digitalization strategies remain environmentally biased [47]. Expanding digital applications to address social dimensions—such as health, safety, and equity, remains a critical challenge for both research and practice.

5.3. Economic sustainability

Economic indicators, including life-cycle costing, resource efficiency, and financial viability, were also weakly associated with BIM and DT. BIM provides tools for cost estimation and scheduling (5D BIM) [10], yet these are not commonly integrated with sustainability metrics. DTs, while enabling predictive maintenance and operational efficiency, have not been systematically applied to financial sustainability assessments. The lack of consensus in this category suggests that digital tools are perceived as less capable of addressing long-term economic dimensions of sustainability. This finding highlights the need for innovation in linking BIM- and DT-generated data with economic evaluation methods, as well as for standards and policies that recognize financial sustainability as integral to sustainable construction.

5.4. Methodological contributions

Beyond these thematic findings, the introduction of the CWS and WAS provided methodological innovations that enhanced the reliability of the evaluation. By weighting responses based on expertise and capturing consensus, these metrics offer more nuanced insights than unweighted surveys. Results showed strong agreement in environmental categories and weak consensus in social and economic domains, reinforcing the interpretation that digitalization is most advanced where measurable, technical indicators dominate.

Taken together, the findings suggest that BIM and DT play complementary roles in operationalizing environmental sustainability but have yet to extend their value systematically into social and economic domains. This imbalance underscores the environmental bias of current digital applications while also pointing to clear opportunities for research, practice, and policy to extend digitalization into the full spectrum of sustainability.

6. Conclusion

This study addressed the challenge of operationalizing sustainability in the built asset industry by consolidating indicators from certifications and standards and systematically mapping them to BIM and DT capabilities.

Three complimentary outcomes emerge. First, the CSM harmonizes 189 indicators into 15 categories, providing a structured basis for evaluating digital applicability. Second, the introduction of CWS and WAS improves reliability by incorporating expertise and consensus into the evaluation process. Third, the mapping of BIM and DT across sustainability dimensions shows a clear imbalance: while advanced digitalization strongly supports environmental indicators, social and economic indicators remain underrepresented.

These outcomes carry important implications. For practice, they confirm the immediate value of BIM and DT in environmental performance while underscoring the need to expand applications into social and economic domains. For policymakers, the CSM provides a reference to identify overlaps and gaps among sustainability frameworks, informing harmonization and targeted regulation. For research, the study offers methodological innovations and empirical evidence that can guide future work toward a more balanced integration of sustainability dimensions.

6.1. Limitations

While comprehensive, the study does have limitations. First, the certification schemes analyzed in this research are geographically concentrated in North America (USA, Canada), Europe (e.g., Germany, UK, Italy, Austria, Switzerland, Portugal, EU-level schemes), and parts of the Asia-Pacific region (e.g., Singapore, Japan, Taiwan, Australia/New Zealand, Hong Kong, India). This results in limited representation from Africa, the Middle East, and Latin America, which may influence the diversity of region-specific indicators captured. In contrast, most of the standards included in the study are international in scope, such as the ISO series, GRI standards, and SASB frameworks, and are designed for global applicability, reducing geographic bias within this subset of the dataset.

As with all research, the study presented in this article is situated: it was conducted in a North American context and is part of a process of standardization and regulation of sustainable development specific to industrialized countries. Consequently, the research objectives and subject matter themselves -BIM practices, digital twins, and sustainable development-favor certain regions of the world at the expense of others, which are considered “in development”. The study’s scope was also shaped by its focus on regions with established sustainability practices, which may limit applicability in areas with different regulatory environments, climatic conditions, and industry norms. While the selection of sustainability indicators was extensive, it may not encompass all relevant factors, particularly emerging issues or those specific to certain local contexts.

The evaluation stages involved a sample of 41 survey respondents and 3 expert interviewees. Participants represented multiple geographic regions (North America, South America, Europe, Asia) and diverse professional backgrounds (BIM managers/coordinators, consultants, engineers/architects, managers, project coordinators, students, and administrative staff). However, the majority of survey respondents were based in Canada and came from the authors’ networks of partners and contacts. This geographic concentration, along with differences in professional domain or technical expertise, may have influenced certain results despite weighting responses by expertise. For instance, social indicators such as labor rights, community engagement, or accessibility may be perceived differently depending on the respondent’s regional and professional context, as well as the maturity of practices and the level of knowledge of the three research topics: the integration of BIM, DT, and sustainable development.

Finally, technological limitations should be considered. BIM and DT tools are rapidly evolving, and capabilities assessed at the time of this study may change as new functionalities emerge. This highlights the need for continuous updating of digital capability assessments to reflect current industry practice. The same applies to sustainable development and the consequences of climate change. Increasingly extreme events require us to regularly reevaluate our understanding of sustainable development and its implications for the three pillars -social, environmental, and economic-in a world that has already surpassed a 1.5 °C increase above pre-industrial levels [141]. Furthermore, related concepts such as circular economy and circular construction are gaining traction in regulations, societal perception, and industry application. The scope of this study was confined to sustainable development in a broad sense, encompassing novel aspects but sometimes only superficially.

6.2. Future research directions

A range of research perspectives has emerged from the analysis of these limitations. First, future research should aim to broaden the geographical scope of sustainability assessments to include regions that are underrepresented in the extant research. While this initial perspective has the potential to elucidate novel limitations and opportunities for development, the CSM being developed using certification schemes and standards predominantly from North America, Europe, and parts of the Asia-Pacific region, it can be adapted for use in underrepresented regions such as Latin America and Africa. Implementation in these contexts would require tailoring indicator definitions and priorities to reflect local environmental challenges, social needs, and regulatory frameworks. Engaging local stakeholders through participatory evaluation processes could further ensure that the framework remains regionally relevant and practically applicable.

Secondly, future research could concentrate on the empirical validation of the CSM matrix and the links between BIM and DT in various real-world projects in different regions of the world. These initial two perspectives would facilitate the continuous updating of sustainability indicators, incorporating emerging issues and innovations. Fourthly, future research could concentrate on a specific aspect of sustainable development, such as the social dimensions of sustainability (1, 2, 3, 4, 5, 7, 11, 16 SG's) [4].

This research should examine and question the existence of potential opportunities related to the use of BIM and DT applications. For example, do BIM space utilization simulations facilitate engagement? To what extent would these simulations allow for the visualization and evaluation of design options that influence the accessibility, safety, and usability of public spaces? By integrating real-time occupancy and usage data, could DT be used to monitor inclusivity and adapt facilities to the changing needs of the community? Further research could focus on the use of BIM for planning emergency response scenarios, assessing indoor environmental quality for health and comfort, and integrating cultural heritage considerations into renovation projects. Thus, research could be aligned with Goals 5 (Gender Equality), 7 (Affordable and Clean Energy), and 11 (Sustainable Cities and Communities) for the construction sector. Additionally, the advent and implementation of novel technologies, including artificial intelligence, machine learning, and the Internet of Things, must be examined within the context of their integration into BIM and DT. A central inquiry pertains to the manner in which these technologies facilitate the assessment of sustainability: What limitations and biases are involved? Are they restrictive or exclusionary for so-called developing countries? Longitudinal studies tracking the long-term impacts of these technologies on sustainability outcomes would provide valuable insights.

Finally, research into the policy and regulatory implications of adopting digital technologies in sustainability practices can guide framework development. In light of the societal challenges posed by such issues, future research endeavors should adopt a more interdisciplinary approach, integrating technical perspectives from the construction industry with sociological, economic, geopolitical, and climate-related insights. The involvement of multidisciplinary teams facilitates the discussion of these issues with policymakers who establish standards and regulations pertaining to technology and sustainable development.

This research enhances the understanding of sustainability in the built asset industry by developing a framework and demonstrating the complementary roles of BIM and DT technologies. Traditionally, 6D BIM has focused on sustainability and lifecycle performance, integrating energy efficiency and operational data into the building model. Ultimately, this study could serve to extend the concept of 6D BIM by increasing the scope of the operationalization of sustainability indicators, including environmental, social, and economic dimensions, as well as by extending digital capabilities by incorporating real-time data integration through Digital Twins. Despite limitations, the study provides valuable insights for industry stakeholders and sets the stage for future research to further integrate digital technologies into sustainable development practices.

CRediT authorship contribution statement

Meisam Jaberi: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Charlotte Dautremont:** Writing – review & editing, Validation. **Erik A. Poirier:** Writing – review & editing, Supervision, Methodology, Conceptualization, Resources.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.114421.

Data availability

Data will be made available on request.

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