Building and Environment 267 (2025) 112131

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Adoption of Life Cycle Thinking: Impact-driven comparative assessment of Japanese construction corporations' trends in practices

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ARTICLE INFO

Keywords:
Environmental decision-making
Adoption of LCT
Impact of LCA in organizations
Resource productivity
Construction corporations' carbon emissions

ABSTRACT

Although life cycle thinking offers a well-founded set of concepts, methods, and tools for organizational contexts, only little is known about its relevance in the construction sector. In this sector, construction corporations are key players. In this work, a novel impact-driven method to assess the adoption of life cycle thinking by construction corporations is introduced. Japan, as a high-income country with a relatively long history of environmental policies informed by material flow analysis, is chosen as the context. Five Japanese construction corporations and respective reporting are used as case studies. Trends in environmental impacts over time of the case study corporations are assessed using two indicators: resource and carbon productivity. In comparison, an automated text corpus analysis workflow is presented to explore the corporate report's life cycle thinking-related content in a meaningful way. Comparing the period of 2014–2018 and 2019–2023, an overall relative increase in framework adoptions (77%) and their integration in corporate categories (85%) in corporate reports indicates its increased procedural relevance among Japanese construction contractors. Findings show how the carbon indicator is embedded in various frameworks and, for instance, reveal an increased relevance of Scope 3 emissions as a framework on a low level. However, Scope 3 is also utilized as a performance indicator. To this end, considerable temporal differences in adoption practices are observed. Finally, a potentially effective corporate adoption model is identified through the comparative research design. The proposed method can be applied to other construction corporations and regional contexts.

1. Introduction

In a recent report by the International Resource Panel [1], the architecture, engineering, construction, and operations (AECO) sector is identified as the critical driver of accelerating resource demand next to the mobility sector. These two sectors altogether account for a three-time increase in material consumption over the last 50 years. This is mainly because there are six times higher material use and ten times higher climate impacts in high-income countries compared to low-income countries. Overall, the AECO sector is responsible for 39% of global carbon emissions, while the 11% share of embodied carbon related to material production has been historically largely overlooked [2]. Thus, the AECO sector is a significant factor in limiting global temperature increase to well below 2 degrees and in taking efforts to stay below a 1.5 degrees increase compared to pre-industrial levels [3]. Well-informed decision-making is needed to target these pressing issues in the AECO sector. Besides urban density and sufficient building use questions, the key elements of current transition pathways are more resource-efficient production [1], longer life cycles of building stocks [4], and material substitutions through up-scaling of bio-based materials [5]. Well-founded arguments to focus on long-term perspectives on the building stock and associated resource flows were pioneered in research at least 25 years ago [6,7] but remained rather ineffective in practice. Therefore, the demand on multiple stakeholders along the construction value chain to act as "reflective practitioners" [8] is still accelerating.

A reason why life cycle assessment (LCA) and life cycle thinking (LCT) have gained traction in the industry in recent years might be associated with the increased interest in carbon pricing. A report from

Abbreviations: AECO, Architecture, engineering, construction, and operation; AIJ, Architectural Institute of Japan; CSR, Corporate social responsibility; ESG, Environmental, social, governance; FY, Financial year; GDP, Gross Domestic Product; GHG, Greenhouse gas emissions; JPY, Japanese Yen; KPI, Key performance indicator; LCA, Life cycle assessment; LCC, Life cycle costing; LCT, Life cycle thinking; MFA, Material flow analysis

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https://doi.org/10.1016/j.buildenv.2024.112131
Received 2 April 2024; Received in revised form 21 June 2024; Accepted 26 September 2024
Available online 21 October 2024
0360-1323/

the Carbon Disclosure Project Worldwide (CDP) shows that companies planning or using internal carbon pricing exceeded US $27 trillion in 2020 and that nearly half of the world's 500 largest companies by market capitalization already included carbon pricing or are planning to do so [9]. However, previous studies showed that voluntary efforts vary considerably in the level of ambition and focus, leading to various roles associated frameworks that are applied in practice to govern the process. On the pathways to net zero, Becker et al. (2024) characterized those frameworks as providing broad scopes of advice versus focusing on single aspects of climate governance [10]. This report concludes with a call for the widespread adoption of best practices in carbon governance to translate visions into actions. Integrating environmental governance by attaching costs to environmental impacts on micro-economic scales comes with a plethora of theoretical problems, as discussed by Gluch and Baumann (2004) [11]. Therefore, next to a life cycle costing (LCC)-based corporate decision-making approach, they propose two other directions of research on environmental decision-making: acknowledging the cognitive skills involved in decision-making by focusing on improving practitioners' understanding of environmental decision-making and extending the system boundaries of LCC by the complementary utilization of LCA. Adopting LCT, which comprises both LCC and LCA, by construction corporations, which play a leading role in the industry of high-income countries, could be one pivotal step towards putting long-term perspectives on the built environment into practice. However, transition studies show that they do not necessarily accelerate in efficacy over time but may present different qualitative challenges and features in each phase [12]. Hence, there is a need for accompanying research in each distinct phase. For instance, despite recent growth in renewable electricity generation, the rate of progress towards deep decarbonization remains slow [13].

This work aims to contribute to the existing literature on organizational LCT by presenting a first impact-driven assessment of LCT adoptions. To do this, a focus is given on carbon emissions and resource productivity. Japan was chosen as the setting for this study because of its reporting landscape: the most widespread reporting subjects include environmental issues of emissions and resources for multiple years, and it presents the second highest number of integrated ESG reporting globally [14]. These reporting features can be explained by a relatively long history of environmental policies informed by material flow analysis (MFA) indicators [15]. This setting allows the work to draw on a novel data set on material input and carbon output from Japanese construction corporations using material flow data (for twelve years) and Scope 3 GHG emissions (for four years). These indicators have been explored extensively on the scale of a single building and more recently also on city [16], national [17], or transnational [18] levels by, for instance, coupling MFA and LCA or using input–output data (such as, based on economic flows). Still, it has not yet been investigated for process-based data from organizations in the AECO sector to the authors' best knowledge. In this way, the work intends to extend the current state of research on the "procedural relevance" [19] of LCT and LCA in the AECO sector. To do this, this work focuses on how Japanese construction corporations adopt environmental indicators and LCT-based frameworks for environmental indicators. Furthermore, the study aims to identify potentially effective best practice examples to derive recommendations for future adoption pathways. Finally, this work demonstrates how construction corporations' indicators and framework adoptions are related to carbon outputs.

2. Background

2.1. Life cycle thinking (LCT) and decision-making

Starting in the late 1960s – in parallel with environmental movements and the first oil crisis – the development of a general system theory was foundational for early studies in the new field of urban ecology dealing with urban metabolisms [20]. At the same time, the idea of LCA was conceived [21]. Despite this long history of methodological developments, a "short-term bias" in decision-making [20] is far from being overcome. Recently, LCA, LCC, and, more generally, LCT have frequently been the focus of scholarly work in organizational decision-making as an extension of traditional product-related LCA [22]. LCT can be defined as the collection of principles applied in life cycle management (LCM), which entails any lifecycle-based methods and principles (e.g., LCA, LCC, sLCA social life cycle assessment, LCD life cycle design) [23]. A whole building LCA is typically conducted by using a set of indicators considering all life cycle phases, ranging from the product stage (phase A), the use stage (phase B), the end-of-life stage (phase C), to the phase of potential benefits and loads beyond the system boundaries (phase D) [24]. Mazzi (2020) showed a general overview of tools and actions for LCT, centering around LCA, environmental labeling, LCC, social life cycle assessment, life cycle sustainability assessment, as well as carbon and water footprints as typical "partial LCAs" that represent the extended core of LCT [25]. Around the core, expert groups, forums, and initiatives, especially through professional bodies and platforms, as well as elaborated instruments, agreements, and guidelines, intend to enhance its integration. Integrating life cycle considerations in corporate organizations is generally conceptualized as an iterative and multilevel process [26].

LCA in policies. Sonnemann et al. (2018) presented an overview of the role of LCA in policies worldwide. They highlighted LCA's main efficacy in policy documents in four ways: design for sustainability (for instance, sustainability labels and certification frameworks), consumer information, product declarations and procurement, waste management, and assessing climate impacts of GHG emissions. For the case of Japan, the type III-based environmental declarations developed within the *EcoLeaf program* (since 2000) and the *carbon footprint program* (since 2008) are highlighted as milestones in policy development. Although the Japanese industry is perceived to be aware of these developments, challenges in stakeholder engagement through increasing costs are seen as prevailing.

Conceptual Critiques. Pryshlakivsky et al. (2021) provided a conceptual exploration of the limits of LCA in organizational decision-making. They derive three key aspects (problem framing, organizational characteristics, and external environment) to be of interest in order to reflect on obstructive constellations while integrating LCA in an organization [27]. Earlier, Gluch and Baumann (2004) discussed inconsistencies and limitations of decision-making based on LCC and emphasized unfavorable influences due to oversimplifications and uncertainties in rational decision-making. Robertson (2016) argued for the need to further improve the connection between LCA and the field of social sciences, especially economics, due to the shift in focus from clean products to sustainable systems [28].

LCA and risk. Dong et al. (2018) explored the relationship between integrating LCA in risk-based decision analysis in different contexts (transportation planning, flood management, and food production and consumption). They concluded a lack of consistency between LCA and other decision-making frameworks [29]. In the context of decision-making in real estate management, a similar observation was made on the differences between process- (e.g. risk management) and object-oriented indicators (economic, social, ecological) that remain vague in many cases [30]. However, in a conceptual inquiry from Kohler (2017), he developed a set of resilience heuristics intended to bridge this gap by guiding the implementation of life cycle perspectives in management practices by focusing on the building stock in the realm of the *risk society* [31]. In the context of public decision-making and rural territory management, Jouini et al. (2018) developed a framework that connects LCA with a participatory approach to overcome data collection issues, interpretation difficulties, and mismatching interests between stakeholders.

Digital LCT-based tools. It is worth mentioning that the literature presents a growing body of studies on digital tool development. Those tools were often intended to improve the integration of LCA and LCC in decision-making processes [32]. In contrast, early studies in the European context on tool development, including energy calculations, have already been published 25 years ago [33,34]. However, their systematic impact in organizational contexts remains largely unknown. Stucki et al. (2021) concluded with a multi-root situation as the cause for LCA's limited use in industrial practice, including data availability, lack of resources, lack of priority, lack of communication, and high complexity of LCA [35]. In addition, the potential for future research on communication, simplified tools, and refined tools, including economic views, could be targeted at fostering a wider application in decision-making. Novel trends on integrating building life cycle impacts in digital tools for the built environment include reused building components [36] as well as game-based approaches [37]. Notably, a recent study demonstrated how complex dynamic LCA approaches can be conducted using large data sets from simple LCA tools and thereby put into practice [38].

LCA frontiers. Although Anand et al. (2017) did not focus on the case of building transformations, they provided several important frontiers in making LCA more relevant in the construction sector [39]. First, certification frameworks that integrate LCA calculations as a part of their systems, such as LEED and BREEAM, were emphasized. The (early) design phase was considered another important part, especially regarding the concept of embodied energy and the well-researched topic of environmental impacts during the operational phase (especially from heating, cooling, and ventilation). Furthermore, integrating digital approaches, especially building information modeling (BIM) workflows, was argued to present the most promising approach to integrating LCA in corporate contexts.

Relevance of LCA. Subal et al. (2024) provided a study on the procedural relevance of LCA in different organizational settings in the European context [19]. They explored the procedural relevance of LCA in decision-making in large international companies and Swiss public bodies, showing that half of the organizations involved frequently use LCA in decision-making. Their analysis included the intended use cases, decision types, factors for decisions, processes, LCA indicators, and obstacles on the path to increased LCA integration. Three relevant studies have been found by the authors that explicitly elaborate on *adoptions* of life cycle aspects in the construction industry [40–42]. Kwofie et al. (2020) identified various social, technical, and policy factors that may improve LCA adoption in the South African construction sector [40]. In contrast, D'Incognito et al. (2014) argued that organizational culture is the most important barrier to the further integration of LCA [42]. Testa et al. (2016) presented an investigation of LCA (non)-adoption in the Italian context [41]. They found the key difference between adopters and non-adopters to be increased awareness. Therefore, they proposed training and educational initiatives for companies and future research that aim to bridge LCA with the fields of communication and marketing. All three studies used expert or stakeholder surveys as an empirical basis.

In summary, most of the presented works on organizational LCT do not consider the specificities of the AECO sector. Studies that focused on the AECO sector and the associated adoption process were mainly concerned with high-level assessments of stakeholder perceptions. Best practices and applicable approaches to better understand the relevance of organizational LCT and LCA in the AECO sector are, so far, largely missing.

2.2. Environmental policy landscape in Japan

In Japan, corporate reporting requirements and efforts continue to accelerate in parallel. Different factors can be attributed to this trend. An increased interest in corporate reporting in Japan is driven by its primary audience of investors closely followed by shareholders and sustainability rating agencies [14]. According to a report from the World Business Council on Sustainable Development, disclosure of environmental data in Japan is more likely to result from mandatory provisions compared to other top 10 countries in terms of GDP [14]. A principles-based *Code of Conduct for ESG Evaluation and Data Providers* issued by the governmental regulator *Financial Service Agency* provides general guidance for actors in the disclosure process.

Regarding resource efficiency, an OECD (Organization for Economic Cooperation and Development) report emphasizes Japan's pioneering role among G7 countries in terms of the 3R concept (reduce, reuse, recycle) [43]. Enforcing this concept, Japan promotes green public procurement with the Green Purchasing Act since 2000, as well as by issuing the *Environmental Reporting Guidelines* which, for instance, specify how to disclose information on material flows [44]. Furthermore, the *Fundamental Plan of Establishing a Sound Material-Cycle Society* entails a national policy intended to "promote measures" on improving material use and disposal with regular updates on the plan since 2003 [45–47]. The plan is based on Japan's MFA data, including natural resource extraction and waste disposal. The third plan, issued in 2010, included specific approaches intended to be promoted in the construction sector, such as life cycle zero emission by joint efforts from clients, architects, and contractors. In addition, encouragements of actions according to the 3R concept are intended to be triggered through market mechanisms within quantitative environmental targets set by regulators [46]. Among targets for recycling and final disposal, the plan included the following indicators in 2015: JPY 420'000 (US$ 2'800)/ton resource input (entitled *resource productivity*) in comparison with JPY 390'000 (US$ 2'600)/ton in 2010 [45] and a decrease in GHG emissions of 7.8 Mio tons CO_2-eq., restricted to the waste sector. While the GHG emissions indicator is given as an absolute figure, the indicator *resource productivity* relates the Gross Domestic Product (GDP) to the material input. Conceptualizing the latter indicator in this way means that an increase in resource productivity may indicate an increase in GDP or a decrease in material input. In contrast, a decrease may indicate a decrease in GDP or an increase in material input. The current fourth plan, issued in 2018, describes the status quo in resource productivity as initially improving, followed by a recent stagnation [47]. It sets new regulative targets and emphasizes joint efforts from actors in local and national governments, research institutions, Non-governmental Organizations (NGOs), and industry by 2025 [47]. The resource productivity is envisaged to be JPY 490'000 (US$ 3'250)/ton material input in 2025. Further, the plan mentions explicitly a focus on improving resource circulation throughout the life cycle of products and services. GHG emissions are included as indicators comprising cyclical use and low-carbon efforts without specifying a quantitative target. A central aspect of optimizing life cycle material flows is properly sharing information on relevant themes such as the material composition of goods, harmful substances, disassembly, and treatment methods.

Japan's mandatory GHG accounting and reporting system requires corporations with over 3'000 tons of CO_2-eq. to annually report their direct and indirect emissions to the Japanese government [48]. Currently, the Japanese calculation methodology for GHG accounting may not be based on LCA as two different calculation approaches are possible: LCA-based calculations using a typical physical inventory (1) or a calculation using emissions unit values based on monetary amounts (2) [49]. . However, this approach intends to boost voluntary efforts based on common data disclosure in line with Japan's intermediate target of reducing GHG emissions by 46% in 2030 and achieving net zero by 2050 [48].

2.3. Large-scale Japanese construction corporations and carbon reporting

Onat et al. (2020) present a macro-level supply chain analysis focusing on the carbon footprint of the largest global construction markets [50]. Based on a review of input–output data analysis of construction sectors and process-based LCAs, Onat et al. (2020) present the largest global construction markets regarding their carbon impact. Comparing China, the USA, India, Japan, and Canada, they found that for all countries, the main emissions in the construction sector can be

Table 1
List of construction corporations with specific data gathered from two publicly available sources: corporate reports and the carbon disclosure project's sustainability ratings of corporations from 2020 and 2021. The Carbon Disclosure Project (CDP) rating represents an aggregated indicator to measure the environmental performance of corporations in terms of four categories (information disclosure, awareness, management, and leadership).

Construction corporation	Employee number	Total revenue[a]	Construction revenue[a]	R&D spending[a]	CDP rating	
	(2021)	(10^9 ¥, 2021)	(10^9 ¥, 2021)	(10^9 ¥, 2021)	(2020)	(2021)
Takenaka	13'212	1263	1155	10	B	A-
Shimizu	19'661	1299	1255	20	B	A
Obayashi	15'470	1988	1861	16	A	A
Kajima	19'295	2084	1934	15	A	A-
Taisei	14'774	1546	1329	17	A	A-

[a] The construction revenues are inflation-adjusted according to World Bank data [55], last accessed May 23, 2024.

Table 2
The Scopes for GHG accounting in Japan are defined in the Japanese Guidelines for GHG accounting [49], referring to the GHG Protocol[a].

Scope	Definition
Scope 1	Direct GHG emissions by the company. This includes fuel combustion and industrial process emissions.
Scope 2	Indirect GHG emissions from electricity, heat, or steam use. This includes the supply by other companies.
Scope 3	Indirect GHG emissions besides Scope 2 based on the corporate value chain. This includes upstream and downstream GHG emissions from other companies that are related to the company in focus. For instance, extraction, production, and transportation of raw materials (upstream), commuting and business travel of employees, and transportation, use, and disposal of goods and products (downstream).

[a] The GHG Protocol [56] is a multi-stakeholder partnership that intends to establish global standards for GHG reporting. The categories for Scope 3 accounting can be defined as [53]: purchased goods and services (1), capital goods (2), fuel and energy-related activities not included in Scope 1 and 2 (3), transportation and delivery (upstream) (4), waste generated in operations (5), business travel (6), employee commuting (7), leased assets upstream (8), transportation and delivery downstream (9), processing and sold products (10), use of sold products (11), end-of-life treatment of sold products (12), leased assets downstream (13), franchises (14), investments(15)).

attributed to the supply chain and associated Scope 3 emissions (see Table 2 for the definitions of Scopes 1, 2, and 3). For Japan, while direct emissions (Scope 1) and indirect emissions due to energy usage result in about 10%, the share of Scope 3 emissions equals about 80%. A detailed analysis of the contributing supply chain sectors shows that about 56% of Scope 3 emissions stem from national supply chains, mainly from non-metallic minerals, metals, electricity, gas, water supply, and construction. In contrast, the rest stems from global supply chains.

A trend towards Scope 3 emission disclosure in Japan has been noticed from 2015 onward [51]. Japanese corporations tend to focus on upstream processes rather than downstream, reflecting a decade of policies on supply chains [51]. Further insights from carbon-related practice are given by the *Carbon Disclosure Project*. Large-scale investors initiated the project with an asset volume of 96 trillion US$. In the *CDP Japan 500 Climate Change Report*, multiple Japanese construction corporations are already assessed [52]. While the 2019 report shows at least four construction corporations among the largest companies in Japan, in 2021, every construction corporation of the so-called *big five* is listed in Table 1 [53]. Although there are currently other major construction corporations in Japan with comparable or even higher revenues, the *big five* have been described as offering comprehensive coverage of construction services and as "dominating the thinking of the Japanese construction sector" since at least the 1990s [54]. The report presents a scoring system of their respective environmental performance, data on Scope 1, 2, and 3 emissions, as well as information on the number of categories reported within Scope 3, internal carbon pricing policies, and quantitative and qualitative scenario analysis. The latest scoring results are shown in Table 1, including key figures of the corporations.

Shimizu, Obayashi, Kajima, and Taisei are reported to include all 15 categories of Scope 3 emissions [53]. However, the data for Takenaka is not publicly displayed in the report, reflecting a limitation of the assessment. Furthermore, the carbon data is not related to a common base such as revenues or built floor area, and therefore, difficulties in the comparisons arise.

2.3.1. Understanding adoptions in corporate reporting

A structuralist perspective from linguistics is transferred to the context of this work to identify and understand indicator and framework adoptions in corporate reporting. Using the same theoretical starting point, Tengblad and Ohlsson (2009) could identify trends in Swedish CSR practices based on data from corporate reports [57]. However, their approach did not emphasize the efficacy of those trends. Generally, structuralism can be understood as the idea of the essentially relational nature of the construction of meanings in a text [58]. This can be illustrated with the concept of semantic fields. For instance, the meaning of *painting* can typically be co-created using terms in the realm of *color*, *composition*, and *light*. In this way, changes in meanings can be traced based on semantic fields. For instance, Lyons uses the example of *driving* encapsulated through *car* [58]. This way, changes in how crucial topics get addressed can be assessed. For instance, if carbon emissions are discussed using the framework of Scope 3, it implies that indirect emissions at the corporate level are addressed, while discussing carbon within the framework of environmental product declarations means that the approach focuses on material production.

2.4. Life-cycle considerations in the Japanese construction sector

Sato and Ikaga (2017) present a historical overview of essential milestones regarding introducing LCT through LCA in the Japanese construction sector [59]. They highlight the role of the *Architectural Institute of Japan (AIJ)* as an organization that has conducted research on LCA since the 1990s and was involved in the release of the *AIJ-LCA* tool. Later, the CASBEE certification scheme was developed by the *Institute for Building Environment and Energy Conservation* in 2002. CASBEE includes a simplified LCA method covering a range of building typologies [60]. In 2014, the Japanese Basic Energy Plan stated the goal of zero-energy buildings (ZEB) for all new buildings by 2030. However, ZEB focuses primarily on the operational stage of buildings. Further, a recent study on the LCA practices in Japan emphasizes the role of the document *LCA Guidelines for Buildings* (title translated by the author) [61].

The document was first published in 1999 by a sub-committee of the AIJ [61]. It is structured into three thematic parts: (1) LCA procedure, (2) LCA for new construction, (3) LCA for other process phases (repair, renovation, operation, end-of-life) [62]. Overall, the increased popularity of LCA in the Japanese construction sector is highlighted. Specifically, providing environmental information for construction activities has been evolving in various schemes in Japan, for

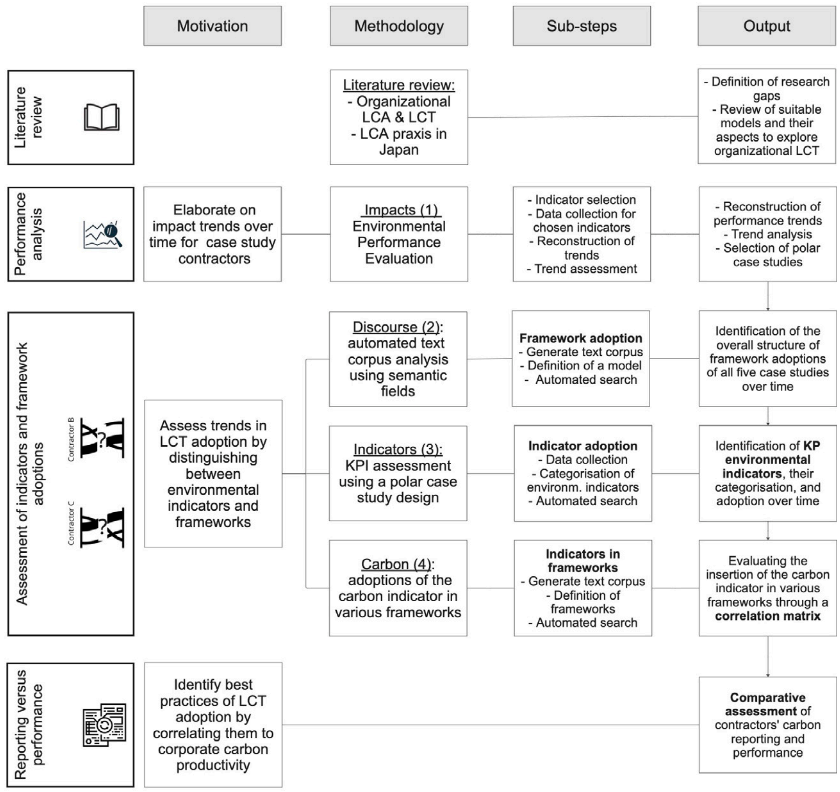

Fig. 1. Conceptual framework of the research method.

instance, CASBEE, LEED, eco-leaf (EPD), and Scope 3 GHG reporting. ISO 14040 (LCA principles and framework) and ISO 14044 (requirements and procedure), Eurocodes for EPDs (environmental product declarations, EN159787 & EN158056) are listed as critical international standards. Multiple background databases are listed as currently in use: IDEA Ver.3, the AIJ-LCA, and 3EID. Additionally, background databases in other countries are listed, such as ecoinvent (Europe) and NREL (National Renewable Energy Laboratory, USA) [62].

3. Research methodology

By definition, descriptions of implemented measures, as well as strategies and visions related to life cycle thinking in corporate reports have no impact on the built environment. The strength of the proposed method is that it allows meaningful extraction of those LCT aspects in corporate reports and that it relates them to associated environmental impacts at the corporate level.

This section introduces the proposed multi-step method and its rationale to assess the procedural relevance of LCT adoptions in corporate contexts. To discuss the efficacy of different modes of adoption, reconstructing real-world environmental impacts by construction corporations (as the investigated organizational unit) is conducted as the first step of the assessment. Trends in LCT adoptions of five construction corporations are structured over time according to the trends in environmental impacts. In this way, the method allows the correlation of LCT adoptions (indicators and frameworks) with impacts. In addition, best practices in LCT adoptions of the *big five* Japanese construction corporations can be identified by focusing on corporate carbon productivity utilizing a newly introduced 3-layer model. Fig. 1 presents the overall methodology. The detailed workflow of the automated text corpus analysis based on the corporate reporting is shown in Fig. 2. The *big five* Japanese construction corporations are selected as case studies, anonymized in the following work. The raw data for each case study is displayed in the Appendix.

3.1. Data collection

Public reports and respective environmental data appendices of the selected Japanese construction corporations from 2010 to 2023 were collected in a comparative case study design. As proposed by Buchholz and Lützkendorf (2022) in the context of real estate [30], we distinguish between environmental indicators and frameworks for indicators. However, it needs to be noted that this distinction cannot always be clearly made. For instance, the analysis shows that certification frameworks are not only used as frameworks for implementing sustainability aspects in construction projects but also as indicators (e.g., an absolute number of achieved sustainability labels in the KPI documentation). The same approach applies to Scope 1, 2, and 3 emissions. Next to these two aspects (environmental indicators and frameworks for indicators), the data-collection process includes environmental impacts based on the KPI data in or attached to the corporate reports. An overview of the data collection process is shown in Fig. 3. As the Japanese financial year starts on April 1 and ends on March 31, for instance, a corporate report from 2023 may reflect the period of April 1, 2022, to March 31, 2023, or in one case, January 1, 2022, to December 31, 2022. The retrieved documents are publicly available on the respective corporate websites. The reported indicators in the documents and the publication formats partially changed over time. For instance, Corporation E published MFA data in a separate CSR (corporate social responsibility) report from 2010 to 2016, while from 2016 onward, the data was published in an integrated report. Additionally, for instance, Corporation E stopped reporting MFA data for timber-based products from 2021 onward. Those changes over time were considered while selecting indicators for the performance analysis to guarantee a consistent data series.

3.2. Performance trend indicators

This work presents time series data on environmental performance trends for five case study corporations in terms of two indicators:

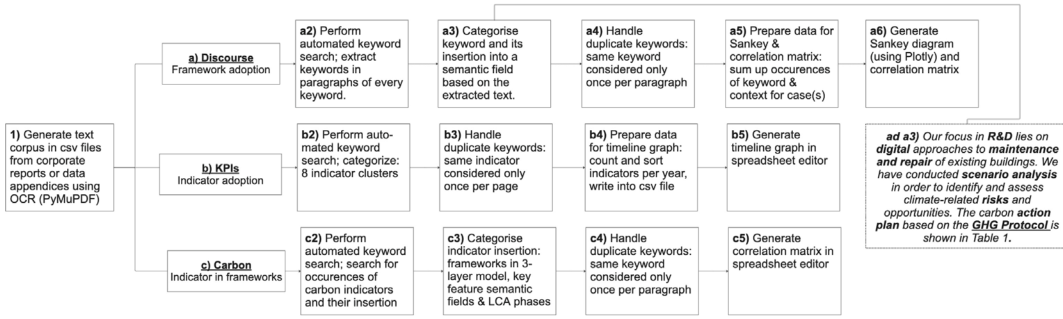

Fig. 2. Representation of the approach to automatically perform a semantic search for indicators and framework adoptions in Python. In the top right corner box, the functionality of the structure detection is schematically displayed. The bold, underlined text represents a detected framework keyword. Bold text shows how the detected keyword is embedded in corporate categories.

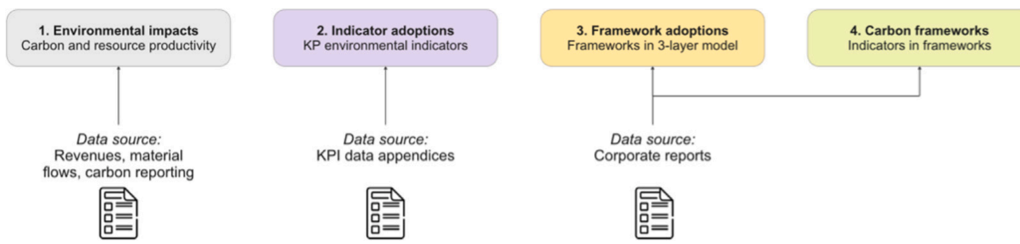

Fig. 3. Structure of data collection process.

GHG emission productivity (JPY 10'000 construction revenue/ton CO_2-eq.) and resource productivity (JPY 10'000 construction revenue/ton material input). The construction revenue can act as a representative reference to relate environmental impacts to an economic context, as a corporation's size (in terms of revenue, employee size, or capitalization) can significantly influence its environmental performance [63]. The construction revenues are adjusted based on Japan's inflation rates for the period 2010–2023. The main material inputs from steel and concrete are considered (asphalt and timber products are not included in the data) based on the MFA reporting of every corporation. For Corporation B, the material input was interpolated for one year within a period of non-fluctuating material inputs (in the year 2012). Similarly, for Corporation E (with an overall non-fluctuating material input pathway), two years were interpolated (years 2017 & 2018). For Corporation C, the material input in one year was calculated based on the amount of materials subject to green procurement and the share of those materials related to the total amount of material input. The MFA data for Corporation B distinguishes between ready-mixed concrete and on-site concrete. From 2016 onward, only the cement content was reported for ready-mixed concrete. Therefore, the total material input from ready-mixed concrete, including cement, water, and aggregates, was calculated based on the assumption of a cement content of 15%.

3.3. Adoptions

In the transition literature, adoptions have been coined in its most general form as the "decision to use and implement a new idea" [64]. To investigate adoptions in the given context, the reports and data appendices of the selected corporations are subject to a systematic quantitative text corpus analysis. Therefore, a coding workflow has been developed in Python [65] using two open-access libraries to (1) create interactive Sankey diagrams (Plotly [66]) and (2) an editable text corpus based on optical character recognition (PyMuPDF [67]). The starting point of the workflow shown in Fig. 2 includes creating text corpora for both aspects, framework adoptions, and indicator adoptions stored in CSV files in a local directory for respective years. Based on these text corpora stored in CSV files, the assessment is conducted. The complete set of search keywords used in the code is shown in the Appendix. Further, in the code workflow respective years of a specific text corpus are identified based on the file name. In this way, the data in corporate reports is referenced with the respective year of the report. For instance, if a project has already been conducted many years ago and is referenced in a current corporate report, the respective project is still handled as part of the corporate activities in the report's year of publication. Further, for indicators specified in the performance data appendices, in multiple cases, data on various years is summarized in a single document. To account for these cases, the respective years where indicators are reported were added manually to the file names to guarantee the correct referencing by the code afterwards.

3.3.1. Indicator adoptions

A polar case study approach is chosen to elaborate on pivotal differences in indicator adoption practices. In contrast to statistical sampling, polar case studies present a theoretical sampling approach, specifically focusing on opposing situations that allow a clear recognition of a process [68]. Therefore, the two case studies that show the most and least promising trends for both indicators (resource and carbon productivity) were selected based on Table 4. Key performance indicators (KPIs) are metrics used to evaluate organizational practices in achieving their strategic or operational objectives. They may provide the basis for decision-making. KPIs are assessed using a longitudinal comparison of KPI categories. KPIs are characterized using the global reporting initiative's (GRI) framework [69]. A simplified version of the GRI indicator structure [70] is adapted to fit the construction sector's specificity properly. For instance, next to the GRI categories of elementary flows (energy, materials), emissions (e.g., Scope 3, NOx, VOC), and so forth, an indicator category for *sustainability labels* is added to conduct the assessment.

3.3.2. Framework adoptions

Based on the linguistic concept introduced in Section 2.3.1, the work analyzes the overall structure of framework adoptions as a form of a discourse among the construction corporations' reports. Additionally, in the second step, the assessment focuses on the structure of carbon-related adoptions. Both parts of the analysis include handling duplicate keywords by including the condition that only one keyword

Table 3
LCT-based frameworks focusing on resources and carbon in corporate reporting based on proposed 3-layer model relevant for construction corporations: materials, buildings, corporation. Sources: (A) [69], (B) [44], (C) [56], (D) [71], (E) [72], (F) [62], (G) [73], (H) [74], (I) [75], (J) [76].

Layer	Types of frameworks	Examples of frameworks	Sources
Layer 3 Corporation	Standards & guidlines corporation	GRI reporting, Environmental reporting, GHG Protocol, ISO 14069, ISO 14064	(A), (B), (C), (D), (E)
	Corporate governance	Life cycle management, CO2 reduction pathway, corporate material flow, Scope 1/2/3	
Layer 2 Building activities	Standards & guidlines buildings	National LCA guidlines, ISO 14040 (LCA), ISO 15686 (Service life planning)	(F), (G), (H)
	Building certifications schemes and tools	CASBEE, LEED, ZEB, Building LCA tools	
Layer 1 Material Production	Standards & guidlines materials	ISO 14067 (GHG), ISO 14025 (EPDs)	(I), (J)
	Product policies	Environmnetal product declarations EPDs (e.g., ecoLeaf)	
Layer 0 LCA	LCA concepts, databases, method	WBLCA (whole building LCA), BLCA, sLCA, LCC, LCCO2, material life cycle, LCI databases (such as ecoinvent), life cycle impact assessment methods (such as IPCC 2021)	

is considered per paragraph. Therefore, the code contains a condition to restrict it to 700 characters before and after a found item, which is intended to represent a standard paragraph length of about 1400 characters. Sankey diagrams and correlation matrices are used to display the results quantitatively. For instance, the code allows to determine how often the keyword *Scope 3* is used by checking how often it occurs in combination with the use of words related to the semantic field of *general trends in the digital realm*. Therefore, in the code, a pre-defined set of words for this semantic field (including, for instance, *artificial intelligence* and *mixed reality*) is included to allow for the identification of its relation to a keyword. Similarly, for evaluating framework adoptions in reporting, the algorithm checks on how often, for instance, the keyword *LCA* is used in the context of the pre-defined semantic field of demonstrator projects (including, for instance, *prototype* and *demonstrated*). Relevant categorizations were defined for both steps, assessing the overall discourse and selected case studies' carbon adoption practices. The overall discourse assessment includes seven corporate categories: demonstrator, governance, vision, risk management, R&D, management commitment, and business model. The assessment of carbon adoptions focuses on the carbon indicator's insertion into various frameworks, as well as an in-depth look into materials, digital technologies, and the whole building LCA concept.

4. Results

The following sections intend to demonstrate how various aspects (impacts, indicators, and frameworks) of organizational LCT contribute to its procedural relevance. The basis of the following assessments is a proposed 3-layer model presented in Table 3. After elaborating on the implications of environmental impacts, an overview of the developments on framework adoptions by the *big five* in the Japanese AECO sector serves as a starting point. Finally, the different aspects of organizational LCT are linked together by focusing on carbon productivity.

4.1. Trends in resource and carbon productivity

Fig. 4 shows the impact trends for five case study corporations in terms of two indicators: (1) resource productivity and (2) carbon productivity. For both indicators, the inflation-adjusted construction revenues relate the environmental impacts to the business performance. Additionally, in Fig. 4(a), a trend line based on the average performance (dashed line) and regulative targets (dotted line) is displayed. A differentiation between trend (increase or decrease in the indicator) and pathway (fluctuating, non-fluctuating, mixed) is considered. The color coding indicates Corporation B as the most suitable polar case on the lower-performance end. In contrast, the results suggest Corporation C to represent the case on the upper-performance end. However, the reconstructed indicator trends could be misleading, for instance, through a substantial increase in revenue, which could still lead to increased resource productivity despite increasing material input. Therefore, single-variable trends (e.g., from inflation-adjusted construction revenues and material input in tons) are also considered (see Fig. 4).

The trends in Fig. 4(a) show an average resource productivity increase until 2018. This trend is not due to single outliers but collective improvements towards the regulatory target for 2015. From 2018 onward, the performance trends are varying depending on the case study. A comparison with the regulative target reflects a narrowing of the gap towards the target in 2015, while only two case studies achieved the target in the following year. After 2018, only two case studies (Corporation A & Corporation D) steadily increased their performance. The trends in Fig. 4(b) present two corporations (Corporation A & Corporation C) that improved their performance in terms of carbon productivity, while one corporation starts from the lowest initial carbon productivity level. A considerable fluctuation characterizes Corporation B's trend. To assess the implications of the trends, a categorization of trends and the single variables (carbon outputs, material input, inflation-adjusted construction revenue) is presented in Fig. 4 to cover the underlying dynamics appropriately.

4.1.1. Construction materials and Scope 3 emissions: An in-depth corporate perspective

A closer look into the environmental data appendices demonstrates the importance of construction materials. The raw data for the following assessment can also be found in the Appendix. For Corporation B, three categories are responsible for 96% of the total 9.36 Mio t CO_2-eq. of Scope 3 emissions in FY2022 (cat. 1 purchased goods and services: 5.7 Mio t CO_2-eq., cat. 4 transportation upstream(corresponds to the life cycle phases A2 and A4): 0.6 Mio t CO_2-eq., cat. 11 use of sold products: 2.7 Mio t CO_2-eq.). The transportation downstream (cat. 9 corresponding to life cycle phase C2) for Corporation B is unrealistically documented as zero. Overall, the case of Corporation C, shows similar

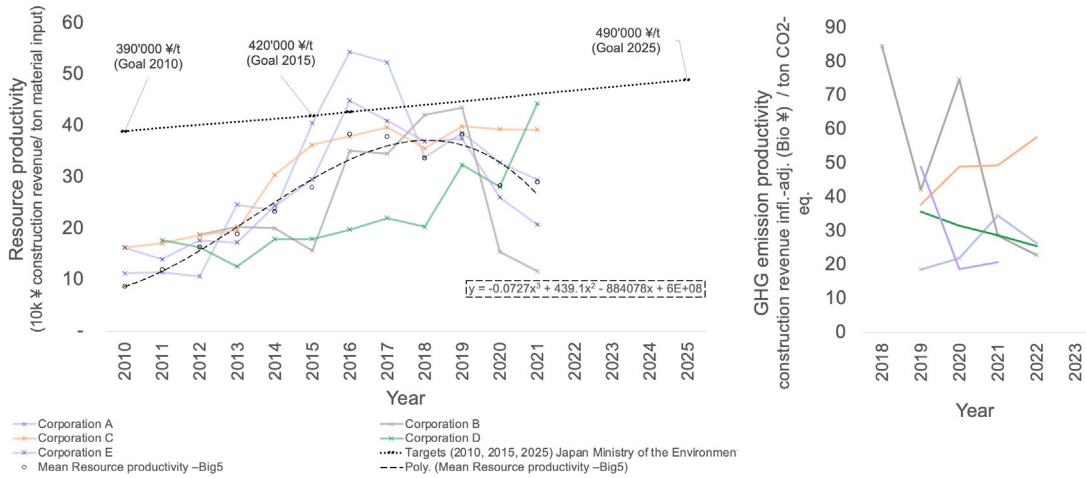

Fig. 4. Reconstructed impact trend lines for five case study construction corporations in Japan in terms of resource productivity (left, a) and carbon productivity (right, b). The color coding in both graphs refers to the respective corporation. The dashed line in (a) represents the average performance trend of all case studies. The dotted line in (a) represents a schematic trend of regulative targets set for 2010, 2015, and 2025 [47].

Table 4
Reconstructed impact trend lines for five case study construction corporations in Japan in terms of two indicators - (1) resource productivity and (2) GHG emission productivity. The codes "mat" and "rev" refer to the variables material input and the inflation-adjusted construction revenue.

	Resource productivity (10^3 ¥/ton material)						GHG emissions intensity (10^3 ¥/ton CO_2-eq.)		
	<2018			>2018			>2018		
Corporations	Trend	Pathway	Variables	Trend	Pathway	Variables	Trend	Pathway	Variables
Corporation A	green	red	mat ↓, rev ↑	red	green	mat →, rev ↓	green	green	GHG ↓, rev →
Corporation B	green	red	mat ↓, rev ↑	red	red	mat ↑, rev ↑	red	red	GHG ↑, rev ↑
Corporation C	green	green	mat ↓, rev ↑	green	green	mat ↓, rev ↑	red	green	GHG ↓, rev ↑
Corporation D	green	green	mat ↓, rev ↑	green	yellow	mat ↓, rev ↓	red	green	GHG ↑, rev ↓
Corporation E	green	yellow	mat ↓, rev ↑	red	green	mat ↑, rev ↓	red	green	GHG ↑, rev ↓

Trend: (red) decreasing, (yellow) stagnating, (green) increasing
Pathway: (red) fluctuating, (yellow) mixed, (green) incremental
Variables: ↑ increasing, → stagnating, ↓ decreasing

characteristics: cat. 1 equals 2.8 Mio t CO_2-eq., cat. 5 equals 0.1 Mio t CO_2-eq., and cat. 11 equals 973 is responsible for 91% of total Scope 3 emissions (4.2 t CO_2-eq.). Transportation is documented with 0.02 Mio t CO_2-eq. (cat. 4, upstream) and 0.06 Mio t CO_2-eq. (cat. 9, downstream) showing a higher impact of downstream transportation processes. The transport emissions for the cat. 9 are calculated as the product of the amount of waste from new construction and dismantling, average transportation distance, and a CO_2 emission intensity factor. The transport emissions for the cat. 4 are calculated based on the procurement results using average transportation distances for each material and fuel emission factors based on the fuel use intensity. For both cases, Scope 3 carbon emissions are responsible for the majority of total carbon emissions (Corporation C: 94%, Corporation B: 98% of all carbon emissions), while purchased goods represent the major impact factor contributing with a share of 2/3 of the total Scope 3 emissions (Corporation B: 61% and Corporation C: 66%). Purchased goods and services mainly refer to the major construction materials used: steel, cement, aggregates, and asphalt.

4.1.2. Characterization of environmental impact trends

Table 4 presents an overview of the characterization of corporate environmental trends. It is worth mentioning that resource productivity before 2018 shows relatively homogeneous improvements among the case studies, while after 2018, considerable differences were noticed. Those differences reflect patterns in terms of the trends of single variables. In all cases, a negative trend in Fig. 4 reflects an absolute increase in the trend of material inputs or carbon emissions. Similarly, a positive trend in Fig. 4 reflects an absolute decrease in carbon emissions or material input. However, in the latter case, with improving environmental performance, at the same time, the business models might tend to get more (Corporation C, resource productivity after 2018) or less profitable (Corporation D, resource productivity after 2018).

4.2. Visualizing developments in framework adoptions using Sankey diagrams

Sankey diagrams in Fig. 5 represent the aggregated structure of framework adoptions of all five construction corporations in two time periods (2014–2018 and 2018–2023). To assess the integration of frameworks in the corporate context, seven pre-defined categories are used (e.g., R&D or risk management). Flows in both Sankey diagrams are scaled according to their respective maximal flow. An apparent overall increase in framework adoptions of 77% is observed (319 and 565 framework adoptions in 2014–2018 and 2019–2023, respectively). Additionally, the integration of frameworks within the corporate categories increased by 85% (505 and 938 connections between frameworks and corporate categories in 2014–2018 and 2019–2023, respectively). However, the increase in framework adoptions only includes minor changes in the types of frameworks, specifically the adoption of EPDs as a framework mentioned frequently in corporate

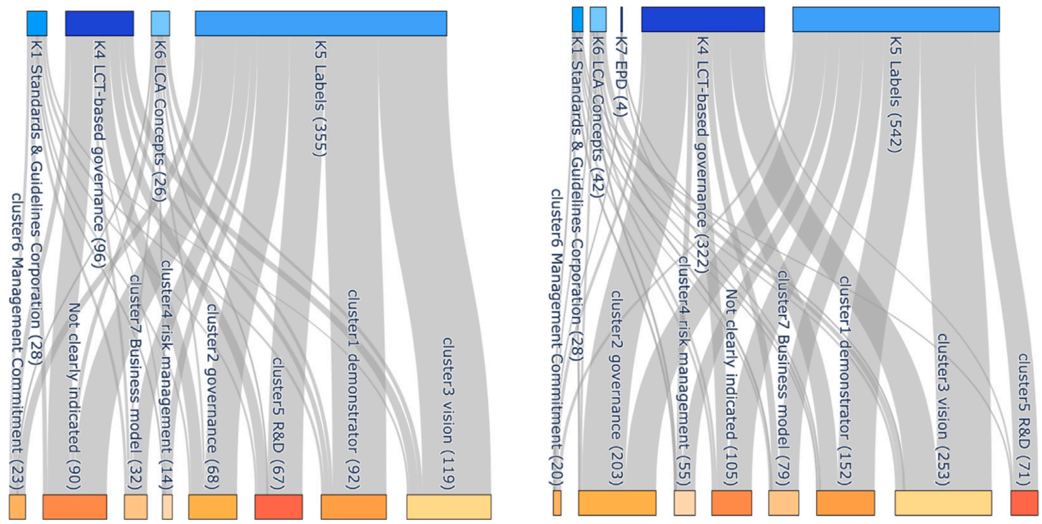

Fig. 5. Aggregated structure of framework adoptions in Sankey diagrams for five corporations for two periods (left figure 2014–2018, right figure 2019–2023). Blue color codes are applied for source nodes, and orange color codes are applied for end nodes.

reporting. The data suggests that environmental aspects of supply chain procurement only gain minor traction. The relevance of environmental R&D decreases while the relevance of LCT-based risk management slightly increases. Comparing the structures of both adoption processes, it can be seen that sustainability labels (and associated rating frameworks) and corporate governance frameworks (especially carbon reduction pathways) present the dominating source node hotspots. In contrast, corporate vision, demonstrator projects, and governance aspects represent the dominant end node hotspots. Correspondingly, the dominant flows between source and end nodes are represented in both periods by label-vision, label-demonstrator, and label-governance connections.

4.3. Trends in indicator adoptions

Fig. 6 shows a comparison of the adoption of environmental indicators for the two selected polar case studies (Corporation B & C) between 2010 and 2022 based on the respective KPI data. An overview of currently used relevant indicators by Corporation C is shown in the caption of Fig. 6. The use of elementary flow indicators for water, materials, waste, and energy consumption stayed constant in the chosen time frame for both case studies. While the considered scope of MFA indicators included the supply chain, this does not apply to water and waste consumption. For energy consumption, the impacts from the supply chain are indirectly considered through Scope 3 emissions. Here, it is worth noting that considerable differences can be observed. While Corporation B only adopted this indicator in 2018, Corporation C reported it already since 2010. The data of both case studies demonstrate an increased relevance of sustainability labels as indicators since 2016. Each considered sustainability label (such as CASBEE and ZEB) is handled as a single indicator in Fig. 6. Recently, Corporation B reduced its number of label indicators compared to Corporation C. Furthermore, a procurement indicator as a share of “green procurement” in total procurement has been used in both performance reporting since 2010.

4.4. Trends in carbon adoptions: a correlation matrix-based approach

Detailed results on the structures of framework adoptions within two periods (2014–2018, 2019–2023) are presented in the Appendix in Table 11 using a correlation matrix. The matrix depicts how the carbon indicator is linked to various frameworks. An overview of the findings generated through the correlation matrix, as well as on indicator adoptions and corporate carbon productivity, is shown in Table 5. Overall, compared to the absolute number of hits, the relative share of the carbon indicator utilized related to Scope 3 emissions doubled on a low level from 2014–2018 to 2019–2023. While 29 connections (3%) were found in the first period, in the second time frame, 148 connections were observed (6%). The matrix shows that all associations of carbon with life cycle phases acquired increased relevance in the second period between 2019 and 2023. Recently, while carbon has been frequently associated with modules A3 (product manufacturing) and B3 (building maintenance), associations with the disposal phase are still dominating.

Regarding the level of buildings, a considerable shift between the two periods can be characterized by an earlier focus on operational carbon towards carbon related to new construction and, lately, the existing building stock. On the material level, carbon is still associated mainly with conventional materials. Nevertheless, the approaches that focus on bio-based or circular materials gain traction on a low level. Regarding technological approaches, barely any attempts were intended to target corporate carbon emissions by introducing digital technologies, digital design, or fabrication between 2014 and 2018. Only recently, the data suggests increased relevance of firstly general approaches, for instance, AI (artificial intelligence), XR (extended reality), MR (mixed reality), AR (artificial reality), or blockchain, by utilizing those approaches to target corporate carbon emissions.

5. Discussion

5.1. Resource and carbon productivity: the role of policies

The Japanese economy showed continuous improvements in resource productivity between 1990–2015 [15,47]; a phase starting around the year 2015 is characterized by stagnation [47]. Our findings on recent trends in resource productivity in the AECO sector based on five construction corporations reflect those economy-wide developments to some extent and indicate that a stagnating trend might have continued or even turned into a decreasing trend since 2018. The trends in carbon productivity also indicate an at least stagnating trend since 2018. A part of the early improvements in resource productivity in the Japanese economy in the 2000s can be linked to national environmental policies [77], introduced in Section 2.2. A specific positive influence of the multitude of regulatory documents issued over a mid-to-long-term time horizon on the resource productivity trend, which was already observed in the literature, can be explained using Geels' multilevel perspective on innovations [78]. “Landscape developments” may pressure industrial sectors as socio-technical regimes, which increase the possibility for “windows of opportunity” where novelties

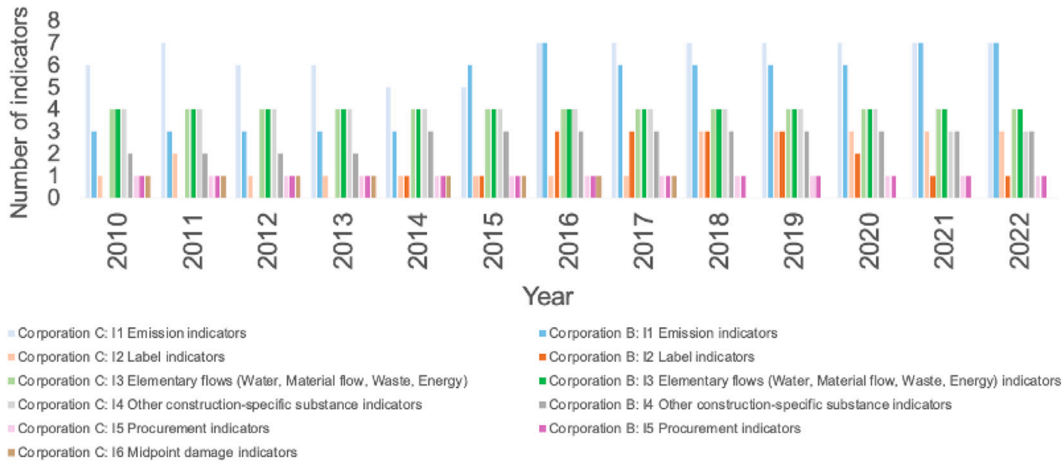

Fig. 6. Adoptions of indicators for two polar case corporations (Corporation B & C) between 2010 and 2023. The detailed list of indicators for Corporation C in the year 2022 is as follows: energy use in TJ (terajoule), resource use in tons or m^3, water use in m^3, waste production in t/type and t/disposal scenario, hazardous emissions (PRTR law substances, asbestos, CFC & halon, PCB in kg), Scope 1, 2, and 3 in tons CO_2-eq., NOx in g, SOx in g, green procurement as a percentage of the total procurement volume, labels (ZEB, LEED, CASBEE as a percentage of the total building activity), environmental law violations in cases.

Table 5
Relative trends in terms of three levels (corporation, buildings, materials) comparing 2014–2018 and 2019–2023 and additional carbon impacts in terms of trends and latest figures (2021) in terms of 10^3 Yen per ton CO_2-eq. Sorted by carbon productivity in 2021 from left to right. Legend: f = framework adoptions, n = new construction, s = building stock transformations, o = building operations, a = alternative materials (bio-based or reused), c = conventional materials, A = LCA phase A, B = LCA phase B, C = LCA phase C, T = LCA phases A2, A4, C4, → stagnating trend, ↑ increasing trend, ↓ decreasing trend. The first occurrence of Scope 3 indicator adoption found in corporate performance reporting: Corporation A (2018), Corporation B (2018), Corporation C (2010), Corporation D (2013), and Corporation E (2020).

			Relative trends				
			C	A	D	B	E
Framework adoptions	Layer 3 Corporation	Corporate frameworks	↑	↑	↑	↑	↑
	Layer 2 Building activities	Building frameworks	↑	↑	↑	↑	↑
		Type of building activity	n→ s↑ o↓	n↑ s→ o↑	n↓ s→ o↓	n↑ s↑ o↑	n↑ s↓ o↓
	Layer 1 Material production	Material frameworks	↑	↑	↑	↓	↓
		Type of materials	a↑ c↓	a↓ c↓	a↑ c↑	a↑ c↑	a↓ c↓
	Layer 0 LCA phases	Life cycle phases: A, B, C	A↑ B↑ C↓	A→ B↑ C↓	A↑ B↑ C↓	A↑ B↑ C↑	A↑ B↓ C↓
		Life cycle phases: transport	T↑	T↓	T↓	T↑	T↓
Indicator adoption	Characterization		innovator	early majority	early adopter	early majority	late majority
	Scope 3 indicator (Year of first adoption)		2010	2018	2013	2018	2020
Impacts	Impact trend		↑	↑	↓	↓	↓
	Carbon productivity in 2021 (10^3 Yen/t CO_2-eq.)		49.4	34.5	28.7	28.6	20.7

can emerge through gradually linking elements in niches. Following this line of argumentation, linking environmental indicators and frameworks on all relevant levels (corporations, buildings, materials) is a crucial next step in transitioning corporate regimes towards life cycle thinking.

5.2. Corporate environmental impacts and LCT: an economy-wide perspective using IPAT

However, drivers of resource use and associated carbon output on an economy-wide scale can have multiple reasons. This has been conceptualized in the Impact Population Affluence Technology (IPAT) formula, developed based on the work of Ehrlich and Holdren (1971) [79]. The formula describes the environmental impact as a product of population size, affluence per capita (for instance, GDP/capita), and a technological factor. The relative magnitude of these single factors differs depending on the geographical region. In the case of the Asian region, research shows that in the period of 2000 to 2024 (net increase of domestic resource extraction of 89%), affluence (92%) was the dominating factor for domestic resource extraction, next to population size (23%), while technical efficiency can be attributed with an offset of −25% [1]. Regarding Japan's recent decrease in its working population due to the falling birth rate and aging population [80], as well as a continuously stagnating trend in GDP/capita after the collapse of the economy in 1991 [47], it can be assumed that the increase due to population size is overestimated as well as the increase due to affluence compared to the numbers presented above. This would indicate that factor T might have increased environmental relevance in Japan in comparison with the outlined average developments in Asia, assuming that technological development continued. This factor T is equivalent to what was later termed as *eco-efficiency*, denoting a ratio of impact per unit of economic output [81]. The utilized indicators resource and carbon productivity describe the inverse of factor T (economic output as the corporate revenue per impact). Thus, the recently observed negative trend in the case study corporations' resource productivity would contribute to an increase in factor T, which in turn would contribute to a diminishing offset in the IPAT equation. If the role of LCA is to guide the decision-making on factor T [82], research focusing on operational decision-making heuristics for LCT has the potential to advance this role and thus act as a facilitator in the economy-wide sustainability transition.

5.3. LCT-based discourse, frameworks, and indicators

The findings of this study on the overall LCT discourse indicate that while the overall number of LCT adoptions in key corporate reporting elements increased in the investigated period, the structure of the adoptions did not change considerably. A study by Stewart et al. (2018) on global trends in LCA integration in corporate sustainability reporting across sectors observed a unique pattern for Japanese CSR reports within Asia from 2000-2015 [83]. They identified a peak of LCA integration in the Japanese industry around 2000, with a steep decline until 2013 and recent stabilization on a low level. However, their results only considered the quantitative quality of adoptions. This study proposes that the qualitative structure of adoptions (which can be quantified to some extent) might be an additional aspect that needs consideration. Further, the results of our study indicate that LCT adoptions (both frameworks and indicators) are again accelerating among the investigated construction corporations. To this end, sustainability labels and rating frameworks currently are found to act as the most relevant environmental frameworks for construction corporations. Further, they are also utilized as key performance indicators. However, it is worth mentioning research that has shown major sustainability labels and associated rating frameworks – which cover 80% of globally certified floorspace – are not sufficiently providing guidance on energy and carbon transparency, nor do they include targets aligned with the 1.5 °C climate target yet [84].

5.4. Carbon frameworks

Regarding the adoption of frameworks, using a correlation matrix based on the proposed conceptual model to explore the specific case of corporate carbon emissions proved to be a valuable approach to identify shifts as well as untapped potentials systematically. This can be illustrated in the case of digital technologies in construction. Robot-oriented design (ROD) already led to successful demonstrator projects of construction corporations in Japan in the 1980s [85]. Utilizing and further developing use cases based on those existing technologies might, therefore, be a potential for corporations to leverage carbon productivity. For instance, corporations could again focus on robots targeting repair and maintenance tasks. However, the results of adopting digital technologies indicate that these existing technologies have not been used to improve corporations' carbon footprints so far.

5.5. Limitations and further research potentials

Limitations of this work include the availability of data, particularly regarding time series data on the indirect emissions of corporations. As reliable Scope 3 carbon emission data have been found in the corporate reports starting in 2019, only short-term trends can be deducted compared to data on resource productivity. Regarding corporate reports as data sources, their level of granularity limits the study's scope. For instance, utilizing the reports as a data source does not allow an in-depth assessment of corporations' LCA practices, such as if consequential or attributional LCA are prevailing or if, for instance, the database ecoinvent or the IPCC 2021 method are utilized as frameworks.

The work draws on the basic structure according to the GRI framework and extends it with construction-specific indicators (such as sustainability labels and associated rating frameworks) for environmental indicators. However, the developed automated code workflow only considers the occurrence of indicator groups (e.g., water use). Detailed indicator assessments within indicator groups (e.g., groundwater withdrawal, water recycling, seawater withdrawal, etc.) can be the subject of further investigations. Extending the script's functionality to this level of detail to analyze indicator adoptions is subject to future investigations.

For the analysis of the structure of framework adoptions, a limitation is given by the selection of the paragraph length and the number of words in each word cluster regarding corporate elements (e.g., the word cluster for *corporate governance*). Further research could explore improvements in the search algorithm, which could be strengthened by testing the sensitivity of conditions for the paragraph length and amount/type of words in each word cluster. Increasing the number of corporate reports as input data to identify paragraphs and word clusters through machine learning could lead to discovering patterns in the structure of adoptions beyond the pre-defined clusters and conditions.

This approach could be combined based on using a more diverse selection of corporations and respective reports, for instance, including small- and medium-sized enterprises (SMEs), which have been out of the scope of this work. Further, this work considered the most relevant frameworks according to a review of regulative documents, focusing on the Japanese setting presented in Section 2. Internationally, a plethora of, for instance, net zero governance frameworks exist, as shown in a recent study by Becker et al. (2024) [10]. Those frameworks and their adoptions in the AECO sector can be the topic of further investigations based on the proposed method.

In addition, relatively recent trends in research, such as sLCA, are included as frameworks but, so far, have not been identified in the corporations' reports, according to this study. Similarly, further assessments could consider in-depth investigations of different life cycle phases, such as transportation, which can considerably influence the overall environmental impacts of major construction materials such as concrete [86]. Future research can adapt the modular code organization of the introduced code workflow to extend the scope of frameworks by including, for instance, net zero governance frameworks relevant to a specific country or region.

6. Conclusions

This work provides a novel impact-driven method to understand the organizational LCT of construction corporations, focusing on corporate carbon and resource productivity. It elaborates insights on adoptions by differentiating between indicator and framework adoptions within a proposed 3-layer model. Regarding an ever-growing landscape of environmental governance frameworks [10], the proposed model proved useful in structuring assessments on organizational levels of construction corporations.

An overall relative increase of 77% in the number of LCT-based framework adoptions in corporate reports from 2014–2018 to 2019–2023 is found, as well as an 85% increase in the integration of those frameworks in corporate categories such as R&D or risk management. This indicates its increased procedural relevance. However, the overall structure of framework adoptions did not change considerably in these periods. This finding suggests there is still a potential to move to modes of LCT integration that consistently address all relevant aspects introduced in a proposed 3-layer model (corporation, buildings, materials). Corporations' practices regarding indicator adoptions reveal an increased range of environmental dimensions considered over time and variations between corporations. The results indicate that the embedding of indicators in corporations has not been handled consistently. Therefore – going beyond carbon emissions in Scope 3 – it is recommended that all indicators are systematically directed towards a precise coverage of related upstream and downstream processes.

The findings show that corporations should still move from the conceptual stages of adoption to implementation, as the carbon productivity trends of three out of five corporations have recently decreased. Further studies that utilize the proposed method for data from corporations in different regional contexts are encouraged. To this end, corporate environmental data disclosure needs to be emphasized. This work demonstrates that carbon and MFA disclosure is detrimental to assessing the impacts of LCT adoptions in the AECO sector.

Finally, a best practice adoption model regarding carbon productivity is identified using the comparative research design. It includes an increased focus on LCT relations to an (alternative) material supply chain, building transformations instead of building operations, and digital technologies as supporting instruments. The latter aspect only shows accelerating rates of adoptions on a low level since 2018. Early actions of construction corporations in future transition phases can be encouraged. Regarding both the environmental and economic dimensions, the findings suggest that the role of corporations as environmental innovators does not necessarily lead to declining revenues.

CRediT authorship contribution statement

Fabian Kastner: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Edwin Zea Escamilla:** Writing – review & editing, Supervision. **Silke Langenberg:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Ming Shan Ng:** Writing – review & editing, Supervision, Conceptualization.

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.

Data availability

Data will be made available on request.

Acknowledgments

This research was supported by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Grant Agreement 51NF40-205604). ETH Zurich provides open-access funding.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.112131.

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