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Integrating Environmental and Economic Perspectives in Building Design

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Abstract: With increasing environmental damage and decreasing resource availability, sustainability assessment in the building sector is gaining momentum. A literature review shows that the related methods for environmental and economic performance, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), show great potential for answering a multitude of questions related to building performance. Prevalent topics are the implications of LCA and LCC for retrofit solutions and the trade-offs between environmental and economic considerations in building design. A detailed review of 30 case studies shows the range of differing result integration methods and sheds light on the use of monetary valuation of environmental indicators for an integrated assessment. While a quasi-dynamic approach, accounting for the changing value of money over time, is common in LCC, such an approach is largely absent from LCA. The analysis of common metrics shows that the studies employ strongly differing system boundaries and input parameters. Moreover, a clear description of the methodological framework is missing in most studies. Therefore, this research develops an "Eco^2" framework, integrating LCA and LCC for application in building design. Potential further developments for Eco^2 building assessment are related to extending the system boundaries by including mechanical systems and end-of-life phases, data collection and structuring, and streamlining the approach for continuous application to all stages of building design processes. Additionally, the influence on design decisions of employing temporal parameters in both LCA and LCC and of choosing particular result integration methods should be investigated further.

Keywords: building life cycle assessment; building life cycle costing; review; framework; environmental cost; integrated life cycle cost and emissions analysis

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1. Introduction

In addition to the undisputed social and cultural value of buildings, the building industry represents a major part of the European economy, contributing to roughly 9% of the gross domestic product (GDP) of the European Union [1] and providing numerous jobs. At the same time, buildings contribute significantly to environmental problems; e.g., they emit 39% of global energy-related greenhouse gases [2]. Therefore, the building industry plays a major role in reducing emissions, while the economic viability of the building sector needs to be ensured.

To capture the full extent of the quality of a building, life cycle thinking (LCT), the concept of taking the entire life cycle of a product or system into account [3], rapidly gains importance in building design, especially for retrofit solutions [4–9]. The three related methods, (environmental) life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (sLCA), aim to achieve the triple bottom line of sustainability, addressing environmental, economic and social issues, respectively [10,11]. All methods have long been recognized to be part of a full sustainability assessment [12,13], a life cycle sustainability analysis (LCSA), striving to increase the sustainability of products and processes. The origins of the three methods do not lie in the building industry. sLCA is the newest method, recently developed as an extension to environmental LCA [14], and therefore less established than LCA and LCC [15]. LCA was first applied to evaluate packaging options [16], whereas the first application of LCC was in supporting procurement decisions by the US Department of Defense [17]. Hence, neither method was developed specifically for buildings, but each has been adapted to introduce the life cycle perspective into the building industry. Despite their relative maturity, neither LCA nor LCC are part of a standard design process [18], because several obstacles prevent their application. Both methods require detailed information about the future building, the development of scenarios for future events and circumstances, and a structure to communicate results to stakeholders. The data intensity of this process prevents their widespread use [19], worsened by the fact that LCA and LCC are currently developed and applied independently. This separation leads to methodological problems and misses opportunities to efficiently evaluate and optimize environmental objectives and life cycle costs in parallel.

Economic factors in a building design process often outweigh environmental considerations. An ecodesign process has been made mandatory for certain energy intense products by the European Union [20], stressing the opportunities of simultaneous energy and cost saving [21]. However, no building materials, rather only appliances and HVAC components, are part of this requirement. In building design, typical budgeting implies that the choice of a more expensive option in one area has to be compensated for by savings in another area. As LCA does not take such budgetary trade-offs into account, there being no set budget for environmental factors, it is difficult for designers and stakeholders to evaluate potential environmental improvements regarding their effectiveness [22]. Considering LCA and LCC in parallel helps to identify which life cycle phases and building parts carry economically viable environmental improvement potential. At the same time, an integrated approach exposes where and when environmental impacts can only be reduced at a high economic cost.

Because of their parallels and synergies, an integration of LCA and LCC has been subject of recent research, particularly in the building industry [19]. This paper provides an overview of the integration of LCA and LCC with regard to buildings, analyzing prevailing topics, integration methods, gaps and challenges. For result integration, we paid particular attention to studies expressing environmental factors in monetary terms, as converting all results to the same unit might provide a common ground for result integration. Based on the literature analysis we developed a framework for integrating LCA and LCC in the design process to bridge the gap and facilitate their use in building design.

2. Method

Firstly, a selective literature review on LCA + LCC (simultaneous LCA and LCC) in general, containing review and methodology papers, served as a basis to reveal common methods, existing frameworks and result integration. Twelve reviews on LCA + LCC or environmental and economic assessment were included, amongst further publications related to methodology. We verified that the referenced literature in the review papers pertaining to the building sector was included in the body of work identified by the subsequent keyword search. The reviews revealed general overarching topics in LCA + LCC research.

Subsequently, we conducted a comprehensive literature search for titles and keywords on Scopus, using, e.g., “LCA AND LCC AND construction”, “LCSA AND construction”, “LCT AND construction” as search terms in April 2021, adding recent publications in October 2021. Additionally, we searched with the term “building” in lieu of “construction” and with the spelled-out terms “life AND cycle AND assessment” etc. Citavi version 6.11 (www.citavi.com, accessed on 18 March 2022) software was used to organize and store literature items. We restricted the search to peer-reviewed journal publications, as these publications have been verified by the scientific community. The initial high number of publications (617 after duplicates were deleted) was then screened to ensure that both LCA and LCC were included; i.e., publications using a LCT or LCSA approach, but not applying LCA and LCC, were excluded from the review (Figure 1). We further reduced the remaining number of publications by filtering out the articles which exclusively concerned themselves with infrastructure and equipment, construction and demolition waste (CDW) or with analysis on an urban level, as we are focusing on the application in building design.

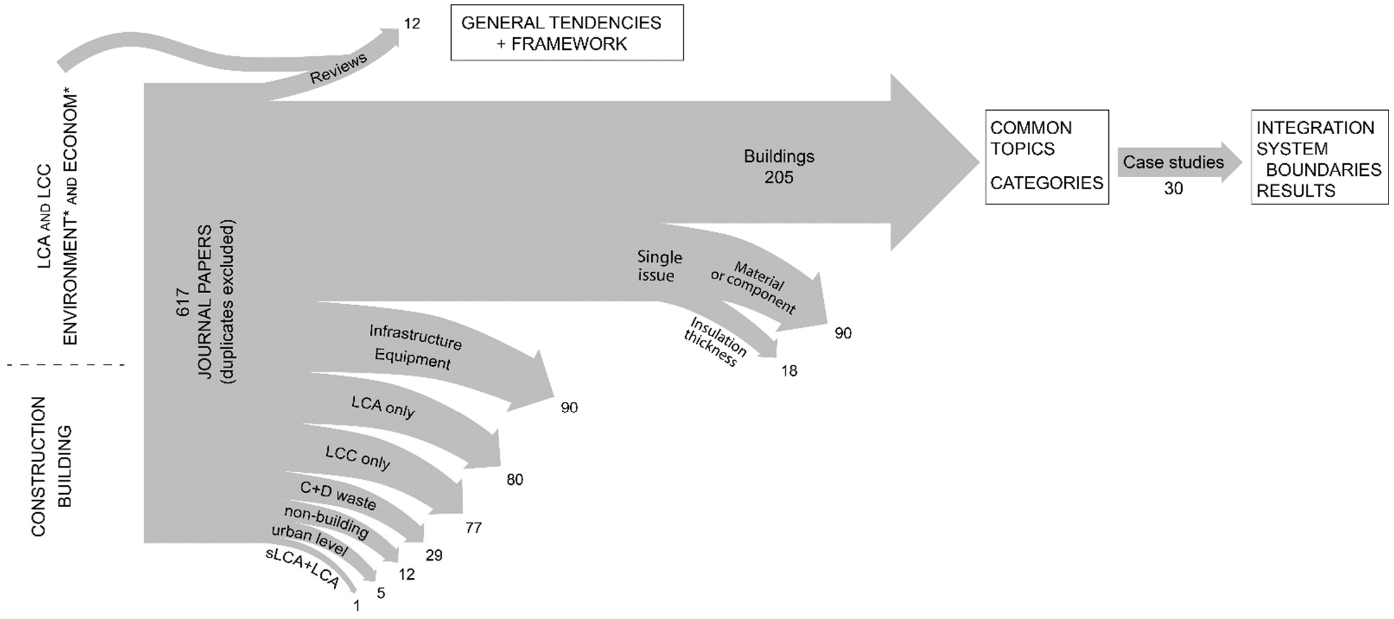

Figure 1. Workflow of the literature review.

In the final step, we investigated if the analysis was performed at the building level or on an element, component, or material level. Of the 108 publications we identified as single issue, 18 dealt with the optimization of insulation thickness based on environmental and economic criteria. The remaining 205 publications were categorized by titles and keywords to find overarching topics in LCA + LCC research.

By reading abstracts and looking for case studies we further identified 30 papers for a detailed analysis to answer the following research questions:

- What are the existing methods and/or frameworks for integrated LCA and LCC in building design?
- Are there common metrics (functional units, life cycle phases, study period) in the previous studies?
- How are results aggregated, compared and/or prioritized to support decisions in the building design process?
- What are the opportunities, challenges and gaps related to an economic-environmental analysis in building design?

As the literature analysis showed a lack of a common framework in existing studies, we developed such a framework to harmonize the methods, identifying parallel steps and synergies, providing a basis for transparency and comparability. Further conclusions from the literature analysis provide information about the steps proposed.

3. Literature Review

3.1. LCA and LCC

Unless only LCA and LCC are considered, they are seen as parts of an overarching goal in connection with other methods: LCA and LCC serve as tools in sustainability assessment [10,23] or in circularity evaluation [24,25]. Earlier reviews [25,26] consider LCA and LCC separately, as using both in parallel appears to be a more recent development. In the building sector, building information modeling (BIM) has been identified as a promising strategy to address the data intensity of the LCA and LCC processes, by aligning input data and managing the data intensity of the process [23,27].

LCA and LCC calculations are complex and require large amounts of data; i.e., their separate use potentially requires double the time and effort and is prone to errors [19]. Even if not fully integrated, their concurrent use, e.g., in the context of the same software tool, could reduce this barrier significantly. However, to arrive at meaningful results, aligning the setup and principles of LCA and LCC is necessary [28]. At the same time, the information about methodology and framework in published studies is very limited, both in LCA and LCC [29,30]. The use of differing frameworks and boundary conditions leads to a wide variation in result values [26], essentially impeding comparability and the transfer of results and experiences between studies.

The high number of recent reviews (Table 1) shows that the topic has received considerable attention, classifying the integration of LCA and LCC broadly into three strategies: (1) approaches using LCA and LCC in parallel at varying degrees of integration, (2) LCA as the leading methodology, including certain environment-related cost aspects, and (3) LCC as the base methodology, including some cost-related environmental aspects [31,32]. Miah et al. [33] extend this to six types of integration, subdividing parallel approaches into the three subtypes (1.1) independent use, (1.2) use as part of an overarching framework and (1.3) use with multi-criteria decision analysis (MCDA) as the integration method. Additionally, they add optimization and eco-efficiency to the picture, which shows that the focus is on the integration and further processing of results rather than the methodology itself. As part of an overarching framework, such as sustainability or circularity, LCA is the most frequently used life cycle method, followed by LCC, which has limited use, and sLCA being very rarely applied [15,24,25,30]. This almost exclusive focus on environmental issues does not sufficiently support implementation of sustainability or circularity, because economic issues act as the greatest barrier [25]. The reviews do not distinguish between the underlying (calculation) methods and the integration and representation of results as a basis for evaluation and, ultimately, for decision making. We add to this body of research by separating the underlying framework from result integration as two distinct but related characteristics. This emphasizes the importance of processing and post-processing results for LCA and LCC to be taken into account in building design processes.

Both LCA and LCC are system-wide approaches, as they share the life cycle perspective; hence, they call for the definition of spatial and temporal system boundaries and the use of corresponding databases [32]. Establishing a common basis aligns the use of data and facilitates the comparability of results. An integrated use has the potential to unify stakeholder perspectives, with LCA focusing on public goods such as human health or ecosystem quality, while LCC includes the (public or private) investor perspective [19,27]. If used in parallel, Hoogmartens et al. [10] recommend using fLCC and eLCA, as this avoids double-counting of impacts.

LCA and LCC results differ in their target values and units. LCA results typically include one or more environmental indicators, resource/energy use or potential environmental impacts caused by emissions. Mid-point impacts characterize emissions compared to a reference substance to show their contribution to a particular environmental problem, e.g., global warming potential (GWP), expressed in kg CO_2-eq. End-point impacts aim at quantifying the impact on areas of protection, e.g., human health, often expressed in disability-adjusted life years (DALY). Despite the large number of possible result values, there is limited use of environmental indicators, with most studies focusing on GWP and/or energy use [23,27,29]. In LCC, the target value is the minimum total cost in connection with an asset for its entire life cycle, measured in monetary terms. Additional possible indicators include the payback period, net savings (NS) or savings-to-investment ratio (SIR) [34]. In the context of building refurbishment, net present value (NPV) or discounted payback period are the most common result values [29].

Table 1. Recent reviews on environmental and economic life cycle assessment.

Title and Reference	Conclusions on LCA + LCC
Bridging the Gap Between LCA, LCC and CBA as Sustainability Assessment Tools [10]	• Identification of different LCA and LCC subtypes (low granularity): environmental, financial, social. • Parallel use of eLCA (environmental LCA) and fLCC (financial LCC) avoids double-counting of impacts.
Life Cycle Assessment and Life Cycle Cost Implication of Residential Buildings—A Review [26]	• Separate analysis of LCA and LCC studies reveals widely varying results.
A Hybridised Framework Combining Integrated Methods for Environmental Life Cycle Assessment and Life Cycle Costing [33]	• Focus on result integration. • Proposed framework: (1) decision-making perspective and goal, (2) system analysis, (3) system integration, (4) graphical interpretation.
Application of Life Cycle Thinking Towards Sustainable Cities: A Review [15]	• Limited LC studies on buildings with focus on economy, none on social issues, many on environmental issues. • Very few integrated schemes.
Exploring Environmental and Economic Costs and Benefits of a Circular Economy Approach to the Construction and Demolition Sector. A Literature Review [25]	• Focus on construction and demolition waste (CDW). • LCA the most frequently used methodology, rarely coupled with other analyses, although barriers to adopt a circular economy (CE) approach are economic.
Informetric Analysis and Review of Literature on the Role of BIM in Sustainable Construction [23]	• LCA, LCC, computational fluid dynamics (CFD) and certification systems are the most used methods for sustainability assessment. • Most studies focus on energy and cost.
Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review [29]	• Few details on the life cycle models used in reviewed papers. • Most prevalent indicators: net present value (NPV), discounted payback period (economic) and life cycle GHG (greenhouse gas) emissions (environmental)
Integrating Life Cycle Assessment and Life Cycle Cost: A Review of Environmental-Economic Studies	• Challenges: time and resource intensive methods; no wide-spread simplification; knowledge intensive. • Opportunities: enablers of great learning opportunities, common system boundaries, common objective and scope, common data collection and set of assumptions, alignment of LC-phases.
Integration of Life Cycle Assessment and Life Cycle Cost Using Building Information Modeling: A Review [27]	• Three main approaches for BIM integrated LCA and LCC: (1) using BIM to obtain bills of quantities and other data, (2) exporting data from BIM model to an external platform, (3) including information within the BIM model. • Energy use and carbon emissions most common environmental indicators for LCA.
Application of Life Cycle Sustainability Assessment in the Construction Sector: A Systematic Literature Review [30]	• LCSA studies focus on environmental issues. • Lack of methodology information on LCA and LCC in studies.
Assessment Methods for Evaluating Circular Economy Projects in Construction: A Review of Available Tools [24]	• LCA the most used assessment method for circularity. • Only one LCA and LCC study in building design identified [9], four studies using cost-benefit analysis (CBA).

To arrive at a single-point result for LCA, weighting is required, which is an optional step in the LCA process [35]. Normalization and/or weighting summarize LCA results, while enabling stakeholders to consider more than one environmental impact. The combination of LCA and LCC results requires yet another level of weighting and/or normalization after the weighting step in LCA, or in combination with it, identifying priorities and potential trade-offs between environmental and economic impacts. For the integration of single LCA + LCC (result) indicators, Huguet Ferran et al. [36] define the following three types: vector optimization, ratio method and weighted addition. Vector optimization graphically represents two indicators in relation to each other and can be used to compare alternatives and to identify dominant solutions. A commonly used ratio method is the calculation of eco-efficiency [37], evaluating economic value versus the environmental burden induced, thereby visualizing the potential trade-offs. Environmental LCC [38,39] is a type of weighted addition as it evaluates the net present cost of real cash flows; i.e., external costs are included if they are internalized or expected to be internalized in the near future. In that sense, it combines LCC and partial LCA, as it does not account for all external costs. All result integration methods except for MCDA need one indicator for LCA results; i.e., they require a weighting step in LCA, if more than one impact category is to be considered. Although weighting is discussed controversially in the scientific community, as it is seen as a value choice [40], it facilitates decision making, and several weighting methods have been developed [41]. Monetary valuation of environmental indicators could be an obvious choice to compare environmental and economic impacts, as it provides results in the same unit. However, it has been only rarely used in previous studies, because it is perceived as very complex, without established rules [19].

The building sector has been the most active of all sectors in the research area related to integrating LCA and LCC [19], as economic factors are seen as barriers for implementation of improved environmental quality [25]. However, all studies mention the lack of an integrated framework, although separate established methods for LCA and LCC exist.

3.2. Building LCA and LCC

Using the identification of overarching topics from the preceding section, all research papers were categorized by their titles and keywords, distinguishing analyses which exclusively used LCA + LCC or did so as part of a life cycle sustainability analysis (LCSA) or as two of the elements amongst methods related to LCT. A few papers did not use LCA but an environmental footprint (EF) method [42,43]. Additionally, two categories, "value" and "circular economy", were identified and added to the picture. The list of papers is available as Supplementary Material S1. Although a significant number of studies perform LCA and LCC in the context of a LCSA or as part of LCT, the majority of the studies state the use of LCA + LCC only (Figure 2). Very few publications mention the related approaches, circular economy (CE), environmental footprint (EF) or the more general term "value". Seven out of ten publications about the use of BIM for LCA + LCC use these two methods only, with three publications using LCA and LCC with BIM for LCSA.

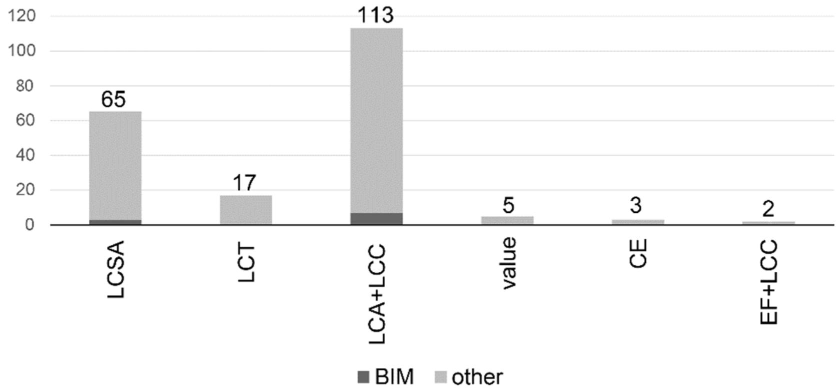

Figure 2. Number of publications on the environmental-economic assessment of buildings by related topic.

Figure 3 shows the rising number of publications in the past decade, as environmental problems are becoming more apparent. The steadily rising number is most apparent in LCSA, but also very visible in the use of LCA + LCC alone. As research into the environmental impacts of buildings has increased considerably in the past years [44], including economic assessments is a reasonable next step. Economic considerations are often cited as an obstacle to environmental improvement, hence the search for the best available trade-off between the two [45]. Although simultaneous environmental and economic benefits are possible, especially in the context of energy efficiency [8,46], none of the studies state this as their primary motivation.

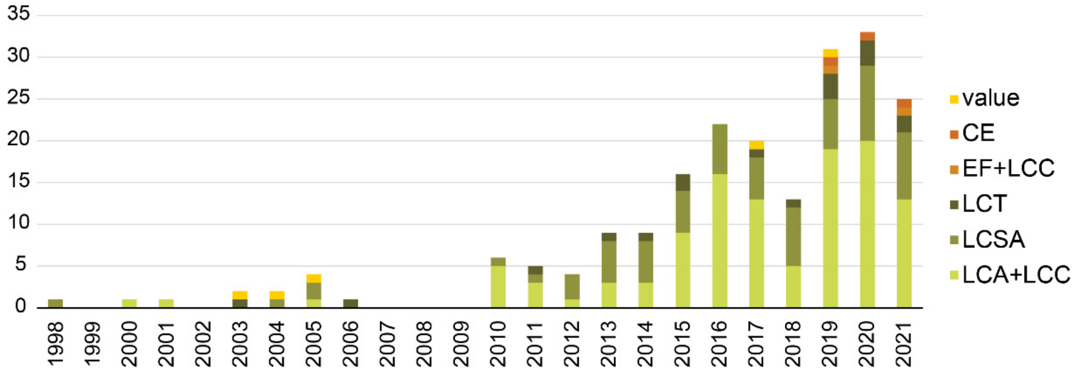

Figure 3. Publications on environmental-economic assessment of buildings by topic and year published.

3.3. Studies on LCA and LCC of Buildings

From the body of literature, we selected 30 studies on the use of LCA + LCC and the corresponding results as performance criteria, which assess one or more sample projects to investigate the potential influence of LCA and LCC criteria on building design (Table 2). Our selection is based on the availability of information about the LCA + LCC process, result integration and boundary conditions. Most case study buildings (21) are residential, with a few mixed-use and some non-residential building types. The subject of half of the studies is new construction, with the other half focused on building retrofit.

Table 2. Case studies on the environmental and economic life cycle assessment of buildings.

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House [47]	50	pre-use use demolition	construction materials appliances	independent, no standards mentioned	payback periods for energy efficiency measures	GWP	accumulated undiscounted cost, PV	DR: 0%, 4%, 10%; interest rate: 7%; energy escalation −1% to 4.2%	juxtaposition
Comparing Life cycle Implications of Building Retrofit and Replacement Options [48]	40	no repair and maintenance no end of life	retrofit: waste new materials; new construction: new materials	independent, no standards mentioned	retrofit or demolition?	GWP, solid wastes, air and water toxicity, resource use	capital cost, annual fuel cost, life cycle cost (NPV)	DR: 7%, energy escalation: 4% (SA with 10%)	juxtaposition, comparison checklist
Life-Cycle Carbon and Cost Analysis of Energy Efficiency Measures in New Commercial Buildings [46]	1, 10, 25, 40	LCA + LCC: construction repair replacement LCA: operation LCC: maintenance energy costs residual values	unclear	independent, no standards mentioned	cost-effectiveness of energy savings measures	GWP, CO_2 cost	NPV, adjusted rate of return (ARR)	DR: 3%	addition of CO_2 costs to LCC
Life Cycle Assessment and Life Cycle Cost Implication of Residential Buildings —A Review [49]	50, 100	construction operation maintenance disposal	no electrical wiring no plumbing no staircase	not specified; common inventory	flooring and roofing options with the best trade-off	GWP, water use, solid waste	NPV	DR: 3% and 6%	juxtaposition
Building Information Modeling Based Building Design Optimization for Sustainability [50]	50	focus on operation	ext. walls	BIM, no standards mentioned	minimize LCC and LCCE (life cycle carbon emissions)	GWP	NPV	real interest rate =−0.507%	multi-objective particle swarm opti- mization (MOPSO), Pareto-optimal solutions
Life-Cycle assessment and Cost Analysis of Residential Buildings in South East of Turkey: part 2—A Case Study [51]	50	LCC: home finance payments construction costs utility payments maintenance service end of life costs	walls flooring roof ceilings foundation basement doors windows appliances electrical systems	independent, no standards mentioned	optimum thickness of insulation	GWP	accumulated undiscounted costs	no discounting or price change	juxtaposition
Cost-Effective GHG Mitigation Strategies for Western Australia's Housing Sector: A Life Cycle Management Approach [52]	50	construction use	envelope	independent; LCA: ISO 14040-44; LCC:AS/NZS 4536:1999	cost-effective GHG emissions mitigation strategies for the construction and use	GWP, carbon tax	PV	DR 7%, inflation 3%	juxtaposition

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Assessment of Residential Building Performances for the Different Climate Zones of Turkey in Terms of Life Cycle Energy and Cost Efficiency [53]	30	A1–A3 B6	ext. walls ground slab roof windows	independent, 15643-2 mentioned for LC stages	optimum improvement of energy performance for different climate zones	GWP	NPV, discounted payback time SA with GWP damage costs	DR 6%, inflation 3,23%, PV degradation	juxtaposition
Construction Solutions for Energy-Efficient Single-Family House Based on its Life Cycle Multi-Criteria Analysis: A Case Study [54]	100	LCA: production/ construction operation maintenance dismantling recycling transportation LCC: investment, replacement costs annually recurring operating, maintenance, repair and energy costs end of life transportation	envelope walls windows doors roof foundations floor plumbing and sewage heating system, ventilation equipment electrical installation	independent, no standards mentioned	find the "best" solution for exterior walls	GWP, ODP	reduction of expenses	not specified	multi-criteria decision analysis
Lifecycle Costing of Low Energy Housing Refurbishment: A Case Study of a 7-Year Retrofit in Chester Road, London [55]	30	energy consumption maintenance repair	ext. walls roof floor	independent, no standards mentioned	compare retrofit solutions, determine payback time	GWP	NPV	DR 3,5%, SA 3,25%	cost per ton carbon saved
A Comparative Life Cycle Study of Alternative Materials for Australian Multi-Storey Apartment Building Frame Constructions: Environmental and economic Perspective [56]	60	LCA: product transportation end of life including CO_2 offset LCC: products manufacturing construction, maintenance demolition transportation final disposal	structural frame	independent; LCA: ISO 14040:2006; LCC:AS/NZS 4536:1999	compare various materials for constructing the structural frame: Laminated Veneer Lumber (LVL), 3 different manufacturing types, concrete and steel	GWP, AP, EP, fossil depletion, human-toxicity potential, carbon tax	NPV	DR 4,9% (SA 3% to 7%), 3% inflation rate (SA 1% to 5%)	juxtaposition, inclusion of carbon tax in LCC
The Influence of Secondary Effects on Global Warming and Cost Optimization of Insulation in the Building Envelope [57]	50	A1–A5 B1–B7 C1–C4 no indication if complete	ext. walls roof ground slab	independent, LCA: DIN EN 15804 mentioned	influence of secondary effects on insulation thickness optimization	GWP	NPV	DR 3% and 7%; energy price increase: index +2%	Pareto fronts

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Building Design-Space Exploration through Quasi-Optimization of Life Cycle Impacts and Costs [58]	25, 50, 100	embedded operational replacement	LCA + LCC: foundation floors ceilings ext. walls ext. finish int. walls roof windows doors LCC: HVAC system	independent, no standards mentioned	flexible design guidance	GWP	cost	no discounting or price change	weighting: minimization of costs, equal weighting of costs and impacts, minimization of impacts
Life Cycle Assessment and Life Cycle Cost of University Dormitories in the Southeast China: Case Study of the University Town of Fuzhou [59]	50, 75	construction operation, maintenance demolition	LCA and LCC: building equipment excluded	independent; LCA: ISO 14040	hot spots and improvement opportunities for university dormitories	ReCiPe midpoints (GWP and nine more indicators)	undiscounted cost	no discounting or price change	juxtaposition
Selecting Design Strategies Using Multi-Criteria Decision Making to Improve the Sustainability of Buildings [60]	100	no end of life	ext. walls roof insulation int. walls	not specified	evaluate design strategies (material choices; insulation thickness)	GWP	Cost savings; initial cost and inflation	not specified	Multi-criteria decision making (weighting by survey)
Streamlined Environmental and Cost Life-Cycle Approach for Building Thermal Retrofits: A Case of Residential Buildings in South European Climates [61]	50	end of life existing production new construction new heating/cooling maintenance	ext. walls and roof insulation and finishes windows	common database, common system boundaries, no standards mentioned	evaluate retrofit strategies in early design	ReCiPe (midpoint; GWP, ODP, AP, EP (marine and freshwater)	NPV and EAC (equivalent annual cost)	DR 1% to 8%	juxtaposition
Houses Based on Wood as an Ecological and Sustainable Housing Alternative-Case Study [62]	50	product construction process use end of life	Foundation vertical and horizontal structures roofing finishes	independent; LCA: EN 15978 LCC: ISO 15686-5	environmental and economic sustainability characteristics of selected construction variants	GWP, AP	NPV	DR 1%, 2%, 5%	juxtaposition
Trade-off Between the Economic and Environmental Impact of Different Decarbonisation Strategies for Residential Buildings [45]	30	product construction process use end of life	building construction building services	independent; EN 15804 life cycle phase definition used	contribution of different strategies to reaching climate goals	GWP	IRR (internal rate of return);	no discounting or price change; linear change of electricity mix emissions; 30% efficiency increase in manufacturing over the next 100 years	Pareto-front

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Life Cycle Assessment and Life Cycle Costing of Container-Based Single-Family Housing in Canada: A Case Study [63]	50	LCA: pre-use use demolition disposal LCC: initial investment operation maintenance repair	structure and finishes	independent; LCA: ISO 14044	life cycle impact of a container-based modular house compared to the conventional lightwood house built in Canada	GWP, AP, ODP, EP; smog potential, HH particulate, solid wastes generation	PV	DR 6%	juxtaposition, equal weighting
Whole Building Life Cycle Environmental Impacts and Costs: A Sensitivity Study of Design and Service Decisions [64]	60	A1-A3 B3-B4 B6-B7 no EoL	Superstructure, ext. and int. walls, roofs, windows, int. ceilings, floors and finishes, MEP of energy and water provision	framework = parallel use in one simulation setup	parametric assessment of building performance: LCA + LCC + energy modeling + seismic assessment	GWP	cost	not specified	separate indicators for LCA and LCC, sensitivity study
A Multi-Objective Optimization Model for Determining the Building Design and Occupant Behaviors Based on Energy, Economic, and Environmental Performance [65]	40	"the whole life cycle"	windows only	independent; LCA: ISO 14040	find optimal design strategies for each season	GWP	significant cost of ownership (incl. savings), NPV	Real discount rates: 2.68% interest growth rate, 0.98% electricity price increase, 1.97% gas price increase	Multi-objective optimization
Life Cycle and Life Cycle Cost Implications of Integrated Phase Change Materials in Office Buildings [66]	50	A1–A3 B6–B7 C1–C4	walls, floors and ceilings of one office unit	common inventory (OneClick LCA); LCA: ISO 14040, LCC ISO 15686;	benefits and costs of PCM in office uses	GWP, AP, EP, ODP, POCP	NPV, discounted LCC	DR 3%, general, energy, water inflation rate 2%	Juxtaposition
Is the Environmental Opportunity of Retrofitting the Residential Sector Worth the Life Cycle Cost? A Consequential Assessment of a Typical House in Quebec [67]	not specified	LCA: unclear LCC: investment, operations, maintenance, end of life	roof insulation, wall insulation, ground slab insulation, heating units	not specified	profitability of retrofit options	Impact 2002+: Human Health, Ecosystem quality, GWP, resources; ReCiPe (for result aggregation)	cost savings	DR 4%	Juxtaposition
Integration of LCA and LCC Analysis Within a BIM-Based Environment [68]	60 years	theory: streamlined (A1-A3) vs. complete (A1-D); case study: not specified	envelope int. walls int. floors	BIM, no standards mentioned	Design support	GWP, AP, EP, ODP, POCP, ADP	NPV	not specified	BIM framework

Table 2. *Cont.*

Title and Reference	Study Period (Years)	System Boundaries; Temporal: Life Cycle Phases	System Boundaries; Spatial: Elements and Processes	Process Integration and Methods	Goal or Research Question	Environmental Impact Indicators (LCA)	LCC Indicators	Temporal Parameters (DR Discount Rate)	Evaluation Method, Result Integration
Simulation-Based Multi-Objective Optimization of Institutional Building Renovation Considering Energy Consumption, Life-Cycle Cost and Life-Cycle Assessment [69]	50	not specified	Building envelope, energy-related systems (LCC only)	BIM, EN 15978 and EN 15804 mentioned for LC phases	optimize renovation strategies	GWP	life cycle cost (not specified)	not specified	Pareto fronts, Decision making; multi-objective optimization
Development of an Approach to Assess the Life Cycle Environmental Impacts and Costs Of General Hospitals Through the Analysis of a Belgian Case [70]	30	LCA: production construction use end of life LCC: investment cleaning maintenance replacements refurbishment operational energy and water use demolition waste treatment	building excl. surroundings	independent; LCA: EN 15804 and EN 15978	main drivers of the environmental impacts and costs of healthcare facilities, identify methodological obstacles for a quantitative assessment.	monetized results (GWP, ODP, EP, POCP, ADPE and 14 other indicators)	NPV	2% financial, 1% growth rate labour, 2% growth rate energy, 1% DR env. cost	total cost
To Retrofit or Not? Making Energy Retrofit Decisions Through Life Cycle Thinking for Canadian Residences [6]	25	LCA: construction manufacture installation operations disposal LCC: capital cost operation disposal	insulation windows energy systems	independent; LCA: ISO 14040	evaluate common upgrades; regional suitability of retrofits	GWP	payback period	DR 3%	eco-efficiency
Development of a BIM-based Environmental and Economic Life Cycle Assessment Tool [71]	50 years, 100 years	A1–A3 (streamlined) B6 excluded	content of the BIM model, MEP excluded	BIM: Common data repository, common inventory; no standards mentioned	proof of concept for LCA + LCC BIM integration	ADPE, ADPM, AP, EP, GWP, ODP, POCP, PENRE, PERT	NPV	DR 3%, 10% (100 years)	BIM; no integration of results
Environmental Costs of Buildings: Monetary Valuation of Ecological Indicators for the Building Industry [72]	50 years	LCA + LCC: A1–A3 B4, B6 C3, C4 D; LCC: B2 B3	structure finishes	parallel use, input aligned; LCA ISO 14040, DIN EN 15804	monetary valuation as a weighting method	monetized results (AP, ADPE, EP, GWP, ODP, POCP.)	NPV	DR 1,5% 2% price increase for building materials and services,	juxtaposition
Life Cycle Thinking-Based Energy Retrofits Evaluation Framework for Canadian Residences: A Pareto Optimization Approach [8]	25 years	LCA: manufacturing use disposal LCC: upfront cost operational cost	envelope energy systems	independent; LCA: ISO 14040	retrofit solution with minimum environmental and economic impacts	GWP	NPV (of operational cost savings)	DR 3%	Pareto optimization

LCA + LCC are applied to answer a wide range of questions, from the determination of payback periods for energy retrofits [47], finding optimal solutions for one building part (e.g., insulation thickness [51]) to optimizing an entire design space [58,64] or a group of building types [45]. Prevalent topics are the implications of LCA + LCC for retrofit solutions [6,48,55,61,67,69,73] and the trade-offs between environmental and economic considerations in building design [45,49,65,69].

3.3.1. Existing Methods and Frameworks

Despite the high number of publications and recent developments in the standardization of LCA and LCC, very few studies mention any standards as a basis for their calculations. For the LCA process, ISO 14040, ISO 14044, the building-specific EN 15978, or the building-product-specific EN 15804 are referred to [6,8,52,56,57,59,62,63,65,66,72]. Only three studies refer to an LCC standard; two Australian studies [52,56] refer to AS/NZS 4536, while one European study [62] refers to EN 15686-5. Moreover, underlying calculation metrics were rarely clearly described and are often missing altogether, making results difficult to interpret. The use of BIM implies an alignment of inventory data and offers the possibility to attach cost and environmental impact data directly to the materials and building parts in the BIM model. Beyond this assumption, the studies using BIM for the integrated calculation of LCA + LCC results [50,68,69,71] do not provide more details on calculation methods than the non-BIM studies considered. This lack of transparency inhibits validation and does not allow for general conclusions; i.e., each study answers its study question with a very specific setup.

Life cycle thinking should consider that buildings and the surrounding conditions change over their long lifetime. This calls for dynamic approaches in both LCC and LCA. In LCC, it is customary to account for the changing value of money over time by a quasi-dynamic approach with constant discount and price change rates. This does not, however, account for changing market or environmental conditions, technological or social improvements. Unlike in LCC, the prevalent method in LCA adopts a static approach, partially because perceived volatility is higher in economic data than in environmental data [19]. More recently, the literature on dynamic LCA has grown [74–76], which accounts for dynamic effects in LCA, including technological improvements [77], carbon uptake over time [78], dynamic occupant behavior [79] etc. In the building industry, most dynamic LCA approaches focus on greenhouse gas emissions, quantifying the changing effect of emissions over time [80], investigating changes in the electricity mix [75,81] or district heating [82] and their impact on operational emissions. Zhang [83] applies a quasi-dynamic approach to LCA by discounting the price of carbon emissions over time. Technological improvements and changes in the energy supply mix not only influence the emission factors for energy consumption directly, but also, indirectly, the emissions from material manufacturing. To quantify such effects on embedded emissions, inventory and impact data is recalculated by Potrč Obrecht et al. [77], showing that changes in the electricity mix can significantly influence GHG emissions embedded in materials. In studies considering both LCA and LCC, dynamic approaches in LCA are rarely present. Mangan and Oral [53] consider the degradation of photovoltaic systems in their environmental analysis. Conci et al. [45] assume a linear decrease in electricity mix emissions over time and a 30% increase in manufacturing efficiency over the next 100 years. Two studies apply discounting to environmental impacts after converting them to monetary values: for GWP only [56], or for a set of indicators [70]. One study considers a price increase for GWP [53]. Hence, dynamic effects for LCA are only rarely applied in environmental-economic calculations. However, if LCA indicators are monetized, discounting and/or price changes can be applied for a quasi-dynamic approach similar to LCC calculations.

3.3.2. Common Metrics

A frequently mentioned advantage of using LCA and LCC in parallel is the use of a common inventory [53,57,65]. This requires common spatial (building parts) and temporal (life cycle phases) system boundaries. Additionally, the study period, reference service lives (RSL) and the functional unit should be the same. In all studies, a common study period was specified for LCA and LCC, ranging from 1 year [46], as part of a sensitivity study, to 100 years [49,69,82,83]. 50 years is the most frequently used study period. Although the functional unit is very rarely explicitly mentioned, it can be derived from result representation. Most studies consider an entire building throughout its lifetime; some studies use one square meter, specifying the area either as living area [51], useful area [59] or useable floor area [72]. Only one study uses one square meter living surface area per year [45]. Although using area as the functional unit should make results more comparable between different buildings or building types, its use is not common. This again underlines the fact that the studies do not appear to aim for general applicability, but to answer specific questions about one building or building type.

The choice of temporal and spatial system boundaries varies strongly between studies, because including only the building parts and life cycle phases relevant for the research question reduces the data requirements for LCA and LCC. For a comparison of different options, this can be sufficient. Any systems which are the same for all options can be excluded, as they are irrelevant to the relative comparison. For instance, some studies are limited to the building skin [52,53,59,61,67,80] or a part of it [65], as they consider its influence on operational energy use, but not on other building systems. However, limited system boundaries miss information on the relevance of the study scope. In addition, if system boundaries are not stated clearly, results cannot be validated or compared with other studies. The temporal system boundaries in most studies are verbally described, often with differing terms for LCA and LCC, e.g., “pre-use” and “initial investment cost” [63]. In most studies, the terms used are vague (e.g., “the whole life cycle” [65], “use” [45,59,63,80]), impeding validation of results. The same holds true for the spatial system boundaries; i.e., the building parts and processes included or excluded are often unclear [46] or described in a non-standardized way. In all but one study [56], which is limited to the structural system, one (e.g., windows [65]) or more elements of the building envelope are included. Two studies include appliances [47,51] and eight studies include energy-related systems. Six of these studies include the respective embedded environmental impacts [6,8,45,54,64,67], whereas two studies include building systems only in LCC calculations [58,69]. In general, very little information is provided on the systems included or variations thereof.

The target values of the different studies show a homogenous picture: in all studies, minimizing GWP is stated as the environmental target (16 studies) or one of the targets (14 studies). Environmental indicators are aggregated to ReCiPe points [84] in two studies [59,61], and to Impact 2002+ [85] values in one study [67], with the rest of the studies using a selection of environmental impacts to represent LCA results, in some cases adding inventory indicators (e.g., energy, water use). In LCC, the prevalent target is minimizing the net present value (NPV), with the use of more than one indicator far less common than in LCA. Two studies use a static approach [51,58] and five studies lack information about temporal parameters (discount rate, inflation rate, price change rate) [50,55,68,82,83]. A few studies concerned with building renovation use payback period [6,53] or cost savings [67] as an indicator, based on PV calculations. Discount rates vary from 1% [61,62] to 10% [71], with both in the context of a sensitivity analysis. More common discount rates are 2% or 3%. Studies varying the discount rate state their strong influence on LCC results [49] and observe that lower discount rates emphasize the cost of building operation [62].

3.3.3. Result Integration

The strategies and results of the economic-environmental building life cycle assessments are not comparable, as each study establishes an individual evaluation framework to integrate LCA and LCC results. Most studies juxtapose one or more LCA indicator(s) and one LCC indicator, implicitly leaving prioritization to their target audience. As such, most studies identify trade-offs between environmental and economic factors without quantifying the impacts against each other. Four studies use Pareto fronts to identify Pareto-optimal solutions [45,50,57,69] and three recent studies employ MCDA and optimization [60,65,86]. An interesting approach is the calculation of life cycle cost per ton of carbon saved [55], as it determines GWP prevention cost of different measures within the building sector (in this case, retrofit options). This result integration is similar to eco-efficiency. It can only be employed if GWP is used as the single LCA indicator, but it reveals win-win situations when both cost and carbon is saved.

GWP stands as the single indicator for environmental impacts in the majority of building-related studies, with four studies [46,52,53,56] using carbon pricing or carbon taxes to monetize GWP results. Two additional studies not included in the detailed literature review use damage costs for carbon [9] or an estimated carbon price from the European Union Emissions Trading System (EU ETS) [87] to integrate results. Two studies add carbon tax or carbon pricing to LCC results to compare options [46,56]. Kneifel [46] concludes that the number of energy efficiency measures providing both life cycle cost and carbon savings increases when adding carbon tax to the life cycle cost equation. In contrast, adding carbon tax to the assessment of design alternatives leaves the number of economically viable options unchanged in [52]. For optimized solutions regarding LC energy use, CO_2 emissions and LCC, overall LCC decreased by a higher percentage compared to non-optimized solutions if carbon costs were taken into account [53]. For the evaluation of different structural materials, adding carbon cost and revenues does not change the ranking of options, neither does a variation in underlying parameters [56], as the option with the lowest life cycle cost shows the lowest GWP too. Hence, it depends strongly on the study setup and the values used for carbon pricing if monetization of this indicator has an influence on results.

From the environmental perspective, monetary valuation of more than one indicator is an indirect weighting method, as it applies monetary values to emissions or impacts to make them comparable. Although expressing environmental impacts in economic terms appears to be an obvious choice to compare or integrate LCA and LCC results from an economic standpoint, only two studies apply this method to more indicators than just GWP [70,72]. Both studies [70,72] conclude that the environmental costs are significantly lower than the corresponding financial costs, but it remains to be seen whether adding environmental cost to financial cost changes the ranking of projects. Our own study [72] finds that, for a set of office buildings, the environmental cost of GWP dominates the total environmental cost of the structure and finishes of these buildings, both for a maximum and a minimum valuation of a set of five indicators commonly used in Germany—GWP, AP, EP, ODP and POCP [72]. The study of Stevanovic et al. [70] analyses one hospital building. Despite the different set of monetary values used and a system boundary including operation, the study also concludes that GWP causes the highest amount of environmental cost amongst the indicators GWP, AP, EP, ODP, POCP, ADPE and ADPF. Therefore, monetizing only GWP appears to currently cover the majority of environmental cost. However, restricting evaluation to just one indicator neglects possible trade-offs with other environmental categories, especially when evaluating design options against one another. Moreover, as this only covers one part of the environmental costs caused, it is problematic when used in the context of an integrated environmental and economic assessment.

Although monetary valuation provides seemingly the same unit for both environmental and economic impacts, hence facilitating comparison and the visualization of trade-offs, two different cost types are displayed: LCC shows the financial cost an investor, owner or user is responsible for; whereas LCA reveals the external costs to society, e.g., for a deteriorating environment. Additionally, the results per emission or mid-point indicator differ strongly between studies [88]. Therefore, if used in a design process, sensitivity towards different valuation methods should be included.

3.4. Challenges and Opportunities

The analysis of 30 building LCA+ LCC case studies show a lack of a framework for an integrated approach on three levels. Firstly, most of the studies lack transparency as to the

LCA and LCC methods used. Secondly, both temporal and spatial system boundaries are not clearly described, as there is no common terminology used, for life cycle phases nor building parts and systems included. Moreover, some of the studies do not align the system boundaries for LCA and LCC, or leave it unclear as to whether the same system boundaries are used for both calculations. Thirdly, the studies show only limited result integration and lack reasoning for the choice of LCA indicators. This lack of a framework misses the opportunity to transfer results and experiences from one study to another, to validate results, and to draw general conclusions. This impedes a wide-spread application in design processes, as it suggests high variation in results and omits the question of whether a change in the framework also changes design recommendations.

If LCA and LCC point in the same direction, i.e., a solution has lower environmental impact and lower life cycle cost, it would be sufficient to use only one of the two methods for decision support. This can be the case with energy efficiency measures (e.g., [46,52]). The challenge of weighting LCA against LCC criteria, i.e., considering trade-offs, arises when the results show diverging tendencies, i.e., if environmentally favorable solutions show higher life cycle costs or low-cost solutions have a high environmental impact. In this configuration, a question of interest would be whether adding environmental cost to (financial) life cycle cost tips the scale towards a more environmental option, and, at which cost values this would be the case. With regard to this question, previous studies have looked into the impact of carbon tax, but no taxes or cost for further environmental impacts.

In an integrated framework, methods can enhance each other. For instance, the common practice of considering temporal parameters for future economic impacts can be included in LCA. Although the amount of emissions of a particular process (e.g., heat generation by fossil fuels) might not change significantly over time, the effect of these emissions can change depending on overall environmental quality. If this quasi-dynamic approach is used after monetizing environmental impacts, it provides an opportunity to treat temporal effects in parallel in LCA and LCC. Similarly, the clear definition of the steps required for LCA fills a methodological gap in LCC.

Opportunities include the integrated use of inventory data and methods (e.g., sensitivity analysis) and minimizing the risks of calculation mistakes due to contradicting data between LCA and LCC. Common challenges, such as uncertainty or complexity, can be treated in one step, identifying their overall relevance to a particular question. The greatest opportunity lies in the fact that integrated LCA + LCC calculations can answer a wide range of questions related to building design and operation, opening up the life cycle perspective for both environmental and economic considerations. This is particularly of interest when LCC and LCA do not show the same tendencies, i.e., if economic barriers exist for the implementation of more environmentally friendly solutions.

4. Integrated LCA-LCC Framework: Eco^2

This study complements previous studies by establishing a general framework for the application of LCA + LCC in the building design process to provide a background for future studies and, ultimately, improve comparability.

Although both methods have undergone standardization in recent decades, LCC lacks a general framework parallel to the steps of LCA established in EN 14040 [35]. However, in the context of the sustainability of buildings and constructed assets, EN 15643-4 [89] specifies the framework for LCC, and EN 16627 [90] the corresponding calculation methods. The parallel standards for the environmental assessment of buildings (EN 14643-2 [91] and EN 15978 [92], respectively) reference the more general EN 14040 [35] for LCA.

In addition to the lack of an integrated framework, the standards do not specify system boundaries, impact indicators, functional units, or calculation methods for individual life cycle phases; neither do they harmonize the interpretation and communication of results. Potential sources for specifications related to building LCA and LCC are building sustainability certification systems. Such systems, however, treat the two methods as separate criteria, impeding joint optimization of environmental and economic factors.

Figure 4 juxtaposes the LCA framework (not building-specific) and the building-specific LCC process, identifying parallel steps, though clarifying that the LCA framework is more general, whereas the LCC process does not so clearly separate the steps into a hierarchy. Impact assessment as a separate step is unique to LCA. Although cost calculation is economic impact assessment, the uncertainties related to impact pathways and associated damages of emissions are absent, as prices are subject to market mechanisms.

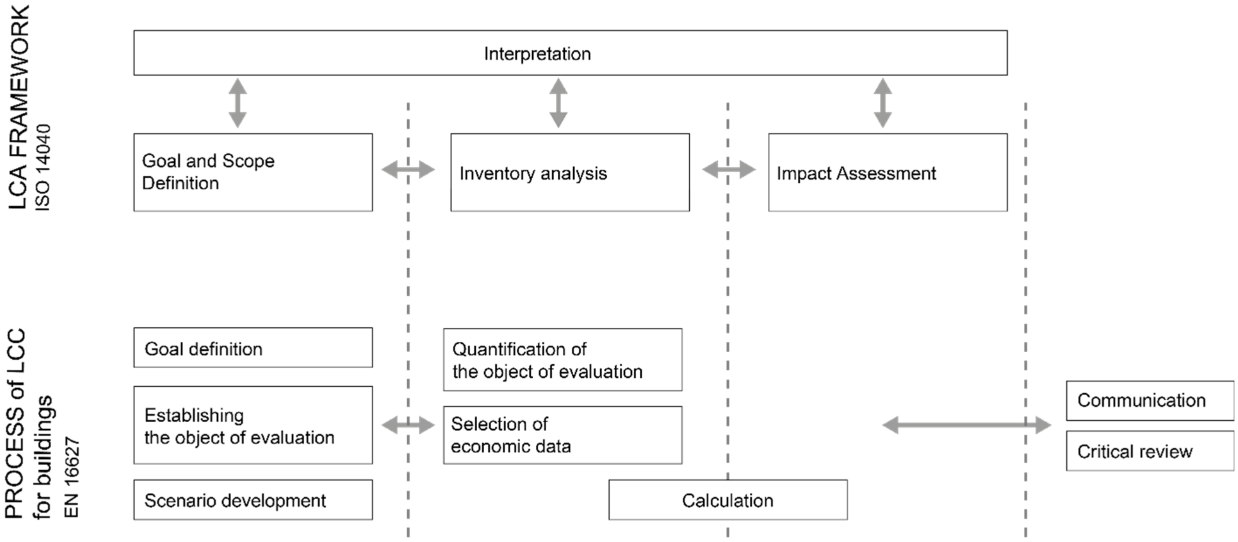

Figure 4. LCA framework per DIN EN 14040 and process of LCC per DIN EN 16627.

We propose to align the LCA and LCC processes, using the general LCA structure, adding methods from the LCC structure to harmonize the methodologies. This "Eco^2" framework developed for future studies integrates LCA and LCC, based on analysis of the literature, to facilitate decision support in building design (Figure 5).

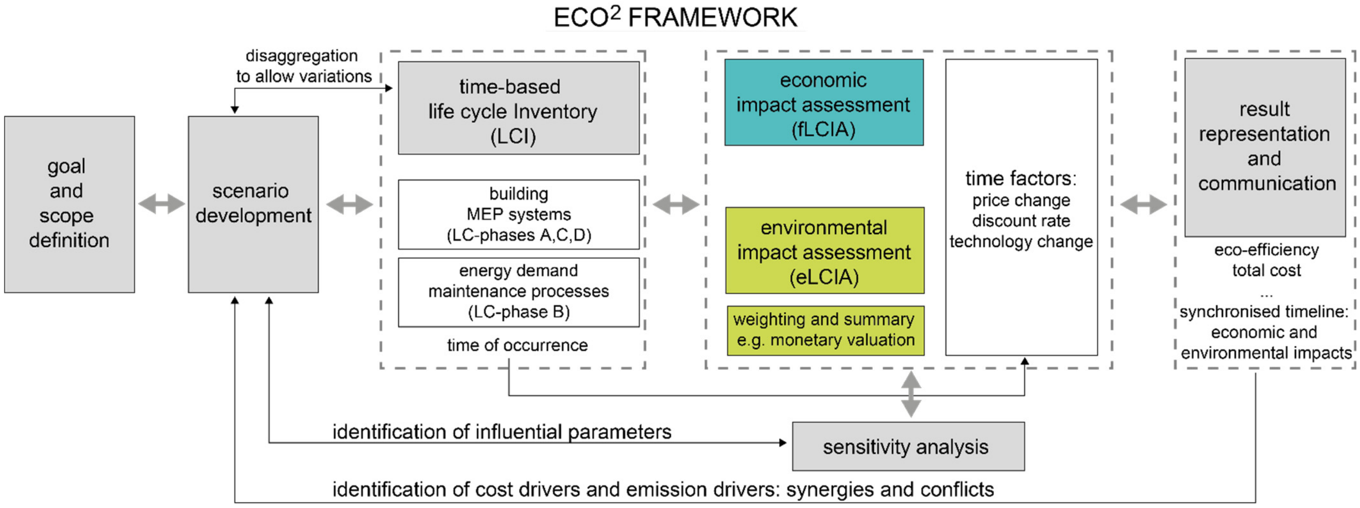

Figure 5. The Eco^2 framework.

LCA and LCC already share a number of common steps and requirements. To fully integrate both, harmonization of every step, as well as aligning both frameworks, makes best use of the opportunities of integration. For this purpose, input data is aligned in a time-based life cycle inventory; i.e., material and energy flows are only calculated once, and subsequently evaluated in environmental and economic terms. In addition, each process is associated with the time at which it incurs costs and/or emissions.

The framework includes weighting and summary of LCA results as one step to make the results comparable, and incorporates the temporal dimension of LCC into LCA. The steps are explained in more detail in the following sections (Sections 4.1–4.5), including conclusions drawn from the literature review in the previous section.

4.1. Goal and Scope Definition

The first step of the analysis defines the goal and scope, for both environmental and economic considerations, harmonizing the specification of the study period, defining equivalent system boundaries and the same functional unit. Especially in building design, the stakeholder group for the environmental aspects (e.g., the general public) often differs from the stakeholder group of the economic analysis (e.g., investor, building user). Harmonizing LCA and LCC aims to integrate both perspectives and enable solutions satisfying both interests. To increase comparability between studies, a detailed description of the system boundaries and the functional unit is recommended.

4.2. Common Metrics and Terminology

Although the life cycle for LCA and LCC is defined in a similar way by the respective standards (Figure 6), some fundamental differences exist. The existence of life cycle phase (module) A0, site and associated cost, in the economic, but not in the environmental life cycle, reveals that this phase might be regarded as irrelevant for LCA. This phase accounts for costs for the site and existing buildings, as well as planning costs. None of the previous studies explicitly included or excluded phase A0, but generally environmental analysis does not consider such site-related impacts, despite the fact that the choice of site might have a strong impact on the later life-cycle phases.

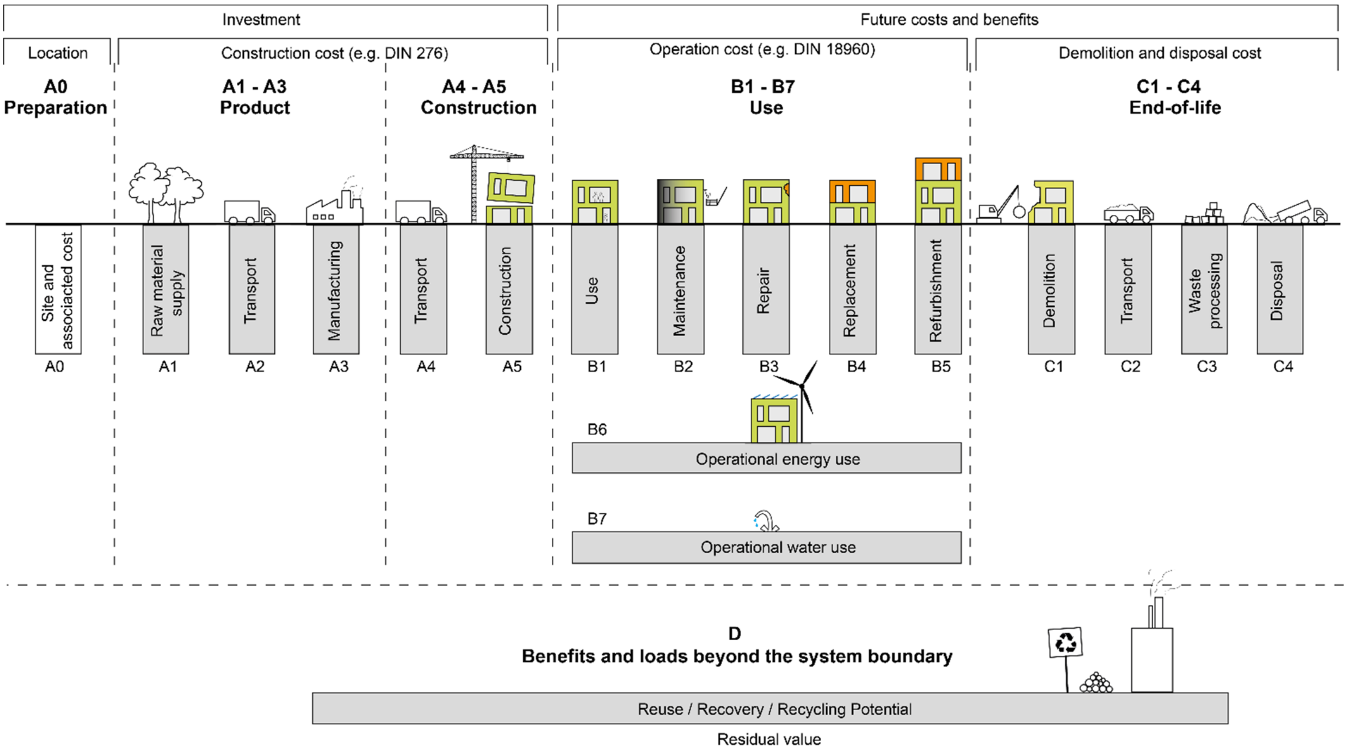

Figure 6. Combined life cycle phases according to BS EN 15978 and BS EN 16627; life cycle phase A0 only in BS EN 16627.

As cost drivers are not necessarily emission drivers and vice versa, different life cycle phases are excluded from LCA and LCC, respectively, as they are considered of lesser importance for one or the other. However, there is a lack of analysis on the distribution of impacts among life cycle phases in the reviewed studies. Few studies assess operational versus embedded impacts and costs, mostly concluding that the operational phase clearly dominates the environmental impact, while investment cost, i.e., production and construction, dominates life cycle costs [57,66,70,72].

Currently, there is no database for calculating all of the life cycle phases; only partial databases have been developed within a research context [61,71]. In general, LCC lacks data on end-of-life phases [25], while LCA lacks data on transport and construction processes, building inspection, repair and maintenance [45]. Data on the construction and use phases is more accessible for LCC, as labor costs largely determine construction processes, cleaning, inspection and maintenance. These are easy to assess economically, but difficult to look at in environmental terms, as labour is typically outside of the system boundary of LCA (e.g., worker commutes, food supply, consumption etc. are excluded). Therefore labour-intensive life cycle phases, such as A5 or C1, are often considered to contribute merely negligible environmental impacts [93], while potentially influencing LCC results [72]. Additionally, these life cycle phases are project-specific, and therefore excluded from, or incompletely included, in standard LCA datasets.

Life cycle phase D (benefits and loads outside of the system boundary) is part of LCA and LCC. Its inclusion in, or exclusion from, overall impacts is often discussed in the recent literature [94], as it is the phase where a circular economy should show its benefits. EN 15643-2 [91] allows phase D to be considered; i.e., this information is optional for environmental assessment. In LCA, materials with a high potential to avoid impacts (e.g., metals) receive many credits in phase D, along with materials serving as secondary fuels (e.g., wood, plastics) [95]. In LCC, materials with a residual value should also receive credits. However, these credits (e.g., for scrap metal) are marginal compared to investment costs [56]. With decreasing resource availability and an increasing interest in circularity, this should change in the future. In the Eco^2 framework, each life cycle phase, including phase D, should be calculated separately to shed more light on the significance of life cycle phases and drivers of impacts.

Decomposition of a building assists data collection, identifying drivers of costs and/or emissions, and supports comparability between studies [96]. Of 12 country-specific standards for building decomposition for the LCA purposes analyzed in [96], 10 are also applicable to cost calculation. The fact that most classification systems are already in use for both LCA and LCC should facilitate the alignment of naming and structure of a building and its sub-elements for Eco^2 calculations.

4.3. Scenario Development and Sensitivity Analysis

Scenario development is a central element of analysis and involves an iterative process. Initially, it is a result of the goal and scope definition, taking into account scenarios that experts deem decisive for economic and/or environmental impacts. Previous studies have investigated energy price change scenarios [47,48,55], decarbonization strategies [45], service decisions [64], PV degradation [53] and monetary valuation models [72]. Sensitivity analyses (SA) later in the process might identify additional influential parameters, calling for adapted or newly created scenarios varying these parameters, e.g., service lives and study period [97] or discount rates [49,56,57,61,62]. In a design process, these analyses can serve to determine the robustness of recommendations by answering the decisive question of whether a change in the framework or related parameters—discount rates, price increases, the inclusion of life cycle phase D, etc.—changes the ranking of possible solutions and, hence, design recommendations.

4.4. Impact Assessment and Two-Step Result Integration

In contrast to LCC results, which are expressed in market value, i.e., as currency, LCA has many possible assessment categories, with different units and without an agreed upon weighting system (see Section 3.3). Separating the weighting step in LCA from the weighting of LCA against LCC results increases transparency in the subsequent evaluation.

As such, the weight of environmental versus economic impacts can be made explicit and discussed. Monetary valuation for the weighting and summary of LCA results is the only calculation method that provides a common (currency) unit for environmental (eLCC) and economic (fLCC) evaluation. However, before simply adding the two values to support decision making, the high variation in monetary values assigned to environmental impacts has to be considered [70,72,88].

4.5. Visualization of Results

Result visualization, interpretation and communication are closely related and an important step towards reaching the initially defined goal of an Eco^2 study. However, result visualization in environmental-economic studies has not received much attention to date. For LCA alone, Hollberg et al. [98] identify 37 different visualization types and provide a comprehensive overview. This analysis can be partially transferred to Eco^2 result representation with the added challenge of visualizing at least two criteria.

Only a few of the reviewed studies did not visualize results, beyond displaying tables with numbers [65,68], whereas most studies used separate bar charts for environmental and economic results, sometimes superimposing results [8,45,52]. A more integrated way of visualizing the trade-off between environmental and economic criteria lies in scatter plots, plotting one LCC against one LCA indicator [8,50,57,58]. This requires one single indicator for economic and environmental results each, and allows for graphically identifying Pareto-optimal solutions. Rarely used visualizations are timelines [51,55,62], parallel coordinate plots [64] and heat maps [71]. These have potential for the comparison of alternatives within a design process and should be explored further.

5. Discussion

5.1. Gaps and Opportunities in the Literature Review

The literature search displayed a high number of studies treating environmental and economic issues in parallel. The large number of studies could only be analyzed regarding the overarching topics that LCA and LCC were applied to, without further details on the exact scope of the study. Our subsequent selection of building LCA studies was based on the criterion that a whole building should be included and that sufficient detail about the LCA and LCC analysis was provided. However, it is possible that other studies providing different insights were excluded if their titles or abstracts did not communicate such results. The 30 studies included should give a good overview of the currently prevalent topics, frameworks, and discussions of LCA and LCC in the building sector, but cannot claim to be a comprehensive overview.

The large number of studies and the increase in recent years reveals that life cycle topics are gaining momentum in the construction sector. More extensive analyses may follow, e.g., regarding the influence of regional factors in results, the influence of temporal parameters or the visualization of results. Our review is focused on, and limited to, the framework and methods, as well as result integration.

5.2. Opportunities and Future Developments of the Eco^2 Framework

We established the Eco^2 framework for building assessment to align environmental and economic life cycle approaches. This is intended to provide a background for future studies to improve comparability of calculations and results. Increased transparency in the methods and better result comparability would enable country- or region-wide comparison of environmental-economic factors, based on aggregated data from Eco^2 studies, as are performed [99] for environmental impacts. As both impacts depend on the surrounding conditions (e.g., electricity mix, energy and material market), decisive factors can differ between countries or regions, influencing recommendations for sustainability strategies.

The Eco^2 framework evaluates the building from a client perspective and is to be used in the design process. This entails that the decision process concerns a choice between materials currently available on the market, as the client does not usually influence the production process of the products. Looking at the results from a supplier perspective reveals opportunities in emissions reduction, which could potentially have larger-scale effects. For building owners and investors, as well as building product manufacturers, Eco^2 can provide a basis for an ecodesign [100] approach, specifically identifying areas for environmental improvement which are economically favorable. In that sense, Eco^2 introduces economic aspects to the ecodesign process. Conversely, Eco^2 complements economic decision making with environmental criteria, revealing decisions which might save financial cost, but cause high environmental impact. If the Eco^2 approach is applied to a scale beyond the scope of a single building, e.g., an entire neighborhood, city or country, it identifies system-wide economically efficient emissions reductions.

Regarding the application of the framework, several gaps identified in the literature review provide potential for further development. Firstly, sensitivity analyses, mostly conducted for price changes and discounting (see Section 4.3), should be aligned between LCA and LCC and extended to further aspects of life cycle uncertainty, namely, service lives of elements, length of study period, environmental and cost data. Secondly, both LCA and LCC calculations are subject to data gaps (see Sections 3.3 and 4.2). In LCA, these concern the life cycle phases specific to a building project—transport, construction, and disassembly (A4, A5, C1, C2)—and MEP systems, for which only a very limited number of studies has been conducted to date. In LCC, data for the value of a material at the end of its use period (phase D) is lacking, as are the costs for disposal or recycling. It is necessary to consider such costs to evaluate a building's potential contribution to a circular economy. Thirdly, the framework provides a structure for Eco^2 evaluation, but it does not remedy the complexity of life cycle calculations. Considering both environmental and economic impacts in parallel remains a data-intensive and time-consuming process. Further work is required to provide robust design assistance for early planning phases, when time and data are scarce, which, to date, has only been tackled separately for LCA [101,102] and LCC [103,104].

A full sustainability assessment adds social LCA (sLCA) to the picture [12], an aspect lacking in the studies to date [15]. The social cost of labor could potentially be significant, especially in the building sector, as it is one of the sectors most prone to labor exploitation in Europe [105]. Additionally, the social cost of construction processes has been highlighted in several studies [106]. The common practice of excluding life cycle phases A5 and C1 from building LCA does not allow the accounting of these costs. As with accounting for the environmental impacts of materials and operation, such considerations might provide a counterweight to LCC, and allow for a broader view on construction activities. However, in sustainability studies, special care has to be taken to avoid the double-counting of impacts, by distinguishing between external and already internalized costs.

6. Conclusions

The literature review showed that the number of LCA + LCC studies has been steeply rising in the past decade, as sustainability concerns in the building sector are becoming increasingly apparent. Most studies related to the building sector use LCA + LCC as a way to identify environmental and economic factors in parallel, followed by a large number of studies which use both methods in the context of life cycle sustainability assessment. Fewer studies adapt a wider perspective, such as life cycle thinking, circular economy, or value. LCA + LCC can answer a wide range of questions related to new buildings, refurbishment, and operation. Most studies state their goal as to identify the best available trade-off between economic and environmental considerations, assuming a dysfunctional market with environmental solutions more expensive than less environmentally friendly ones. Nevertheless, simultaneous environmental and economic benefits are possible, especially in the context of energy efficiency. It is these win-win solutions that bear the potential of increasing the sustainability of the construction sector by reducing environmental and economic burdens in parallel.

Presently, investigation of life cycle environmental and economic impacts for buildings in parallel is time-consuming and requires expertise in both LCA and LCC, which limits the application of an integrated approach to research studies and causes life cycle impacts to be mostly disregarded in design processes. The literature review showed a large variation in system boundaries and frameworks, as each study is set up to answer a particular question, specific to the building type and location under investigation. However, even in a research context, studies lack transparency and clear frameworks, and are rarely applied to overall design questions, limiting their comparability and overall applicability. Our study proposes the Eco^2 framework to facilitate the process by harmonizing environmental and economic calculations, to increase transparency and transferability. Design alternatives can thus be developed for Eco^2 rather than for LCA and/or LCC in an isolated way, and provide leverage towards environmentally favorable solutions, especially if they prove to be economically sound as well. Additionally, the Eco^2 framework offers a way to clearly communicate and discuss the cost and benefits of emissions reduction. In this framework, the gaps in previous studies could be systematically filled. Firstly, system boundaries can be extended to elements and life cycle phases which are, to date, rarely included in studies, such as including MEP systems and interiors, or end-of-life phases. Secondly, data collection and structuring are important topics, both for inventory as well as environmental and economic impact data. This can be instrumental in, thirdly, streamlining the approach for continuous application to all stages of building design processes, at increasing levels of development. Lastly, sensitivity analyses should be systematically applied to investigate the robustness of decision support. In this context, the influence on design decisions of employing temporal parameters in both LCA and LCC, and of choosing particular result integration methods, should be investigated further. Our next step is to apply this framework to a case study including design options for building structure and finishes, as well as mechanical systems, and to test the influence of different parameter choices on design recommendations.

Against the backdrop of recent developments regarding, for instance, the introduction of CO_2 taxes, first steps towards an internalization of external costs for environmental degradation and damage have been taken. Eco^2 creates an integrated life cycle evaluation methodology, which has the potential to support the urgent transformation of the building sector towards a fundamentally sustainable built environment.

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Abbreviations

ADPE	abiotic depletion potential for non-fossil resources
ADPF	abiotic depletion potential for fossil resources
AP	acidification potential
BIM	building information modelling
CBA	cost-benefit analysis
CFD	computational fluid dynamics
CDW	construction and demolition waste
CE	circular economy
EF	environmental footprint
eLCC	environmental life cycle costing
EP	eutrophication potential
FEP	freshwater eutrophication potential
fLCC	financial life cycle costing
GHG	greenhouse gas
GWP	global warming potential
HH	human health
HVAC	heating, ventilation, air conditioning
LCA	life cycle assessment
LCC	life cycle costing
LCCE	life cycle carbon emissions
LCSA	life cycle sustainability analysis
LCT	life cycle thinking
MEP	mechanical, electrical, plumbing
NPV	net present value
NS	net savings
ODP	ozone depletion potential
POCP	photochemical ozone creation potential
PV	present value
RSL	reference service life
SA	sensitivity analysis
SIR	savings to investment ratio
sLCA	social life cycle assessment
TAP	terrestrial acidification potential

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