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Sectorial Investigation of Life Cycle Sustainability Assessment in the Context of Case Studies

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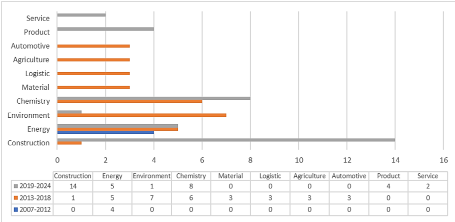
Sürdürülebilirlik
Yaşam Döngüsü Sürdürülebilirlik Değerlendirmesi
Yaşam Döngüsü Değerlendirmesi
Yaşam Döngüsü Maliyetleme
Sosyal Yaşam Döngüsü Değerlendirmesi
Vaka Çalışmaları

Graphical/Tabular Abstract (Grafik Özet)

Life Cycle Sustainability Assessment (LCSA), used in the analysis of sustainability, aims to provide a more holistic approach by considering environmental, economic, and social dimensions. In this study, a literature review was conducted up to June 2024. The findings highlight that LCSA is widely used in the construction and energy sectors, but has lagged behind in product design. / Sürdürülebilirliğin analizinde kullanılan Yaşam Döngüsü Sürdürülebilirlik Değerlendirmesi (LCSA), çevresel, ekonomik ve sosyal boyutları dikkate alarak daha bütüncül bir yaklaşım sunmayı hedeflemektedir. Bu çalışmada, 2024 Haziran ayına kadar literatür taraması gerçekleştirilmiştir. Bulgular, LCSA'nın inşaat ve enerji sektörlerinde yaygın kullanıldığını, ancak ürün tasarımında geride kaldığını vurgulamaktadır.



	Construction	Energy	Environment	Chemistry	Material	Logistic	Agriculture	Automotive	Product	Service
2019-2024	14	5	1	8	0	0	0	0	4	2
2013-2018	1	5	7	6	3	3	3	3	0	0
2007-2012	0	4	0	0	0	0	0	0	0	0

***Figure A**: Frequency of LCSA Methods Application Across Various Sectors by Year /**Şekil A:**. Yıllara Göre Çeşitli Sektörlerde LCSA Yöntemlerinin Uygulanma Sıklığı*

Highlights (Önemli noktalar)

- *The research analyzes the applications of LCSA across different sectors by examining 70 academic studies that include case studies. / Araştırma, vaka çalışmaları içeren 70 akademik çalışmayı inceleyerek LCSA'nın farklı sektörlerdeki uygulamalarını analiz etmektedir.*
- *While LCSA is widely used in the construction and energy sectors, it has a low adoption rate in the field of product design. / LCSA, inşaat ve enerji sektörlerinde yaygın olarak kullanılırken, ürün tasarımı alanında düşük bir kullanım oranına sahiptir.*
- *Factors such as rapid consumption, short product lifespans, and costs make it difficult to adopt LCSA in product design. / Hızlı tüketim, kısa ürün ömrü ve maliyet gibi faktörler, ürün tasarımında LCSA'nın benimsenmesini zorlaştırmaktadır.*

Aim (Amaç): *The aim of this study is to examine the use of LCSA in the literature and to identify its applications in various sectors. / Bu çalışmanın amacı, literatürde LCSA kullanımını incelemek ve farklı sektörlerdeki uygulamalarını belirlemektir.*

Originality (Özgünlük): *This study provides a detailed analysis of LCSA's applications across various sectors, highlighting the low adoption of LCSA in product design. The focus on this specific issue in the existing literature adds originality. / Bu çalışma, LCSA'nın çeşitli sektörlerdeki uygulamalarını detaylı bir şekilde analiz ederek, ürün tasarımı alanında LCSA kullanımının azlığına dikkat çekmektedir. Mevcut literatürde bu konuya özel bir vurgu yapılması özgünlük sağlamaktadır.*

Results (Bulgular): *The findings indicate that LCSA is extensively used in the construction, energy, and chemical sectors, but is limited to only 4 studies in the field of product design. / LCSA'nın inşaat, enerji ve kimya sektörlerinde yoğun bir şekilde kullanıldığı, ancak ürün tasarımında yalnızca 4 çalışma ile sınırlı kaldığı bulunmuştur.*

Conclusion (Sonuç): *This study emphasizes that LCSA should be more widely adopted in product design processes. The integration of LCSA at early stages is critical for achieving sustainability goals. / Bu çalışma, LCSA'nın ürün tasarımı süreçlerinde daha yaygın bir şekilde benimsenmesi gerektiğini vurgulamaktadır. LCSA'nın erken aşamalarda entegrasyonu, sürdürülebilirlik hedeflerine ulaşmak için kritik öneme sahiptir.*

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Abstract

The emergence of the concept of sustainability has brought with it the challenge of measuring this complex idea. Over the years, various methods have been developed to assess the environmental impacts of sustainability through Life Cycle Assessment (LCA), evaluate its economic impacts using Life Cycle Costing (LCC), and analyze its social impacts through Social Life Cycle Assessment (S-LCA). Life Cycle Sustainability Assessment (LCSA) seeks to provide more holistic and comprehensive results by integrating these three dimensions of sustainability. This study examines the role of the LCSA approach in the literature and its application across different sectors. Case studies from various sectors, along with the methods used in these assessments, were analyzed. The findings indicate that the construction and energy sectors account for the majority of case studies employing the LCSA method, whereas the product design sector lags behind. Evaluating the sustainability of products before mass production is critical for achieving sustainable product design. Therefore, increasing the use of LCSA in product design is considered a significant step towards achieving sustainability goals.

Vaka Çalışmaları Bağlamında Yaşam Döngüsü Sürdürülebilirlik Değerlendirmesinin Sektörel İncelemesi

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Öz

Sürdürülebilirlik kavramının ortaya çıkışı, bu karmaşık fikrin ölçülmesi zorluğunu da beraberinde getirmiştir. Yıllar içinde, sürdürülebilirliğin çevresel etkilerini Yaşam Döngüsü Değerlendirmesi (LCA) ile, ekonomik etkilerini Yaşam Döngüsü Maliyetlendirme (LCC) ile ve sosyal etkilerini Sosyal Yaşam Döngüsü Değerlendirmesi (S-LCA) ile değerlendirmek için çeşitli yöntemler geliştirilmiştir. Yaşam Döngüsü Sürdürülebilirlik Değerlendirmesi (LCSA), sürdürülebilirliğin bu üç boyutunu birleştirerek daha bütüncül ve kapsamlı sonuçlar sunmayı amaçlamaktadır. Bu çalışma, LCSA yaklaşımının literatürdeki rolünü ve farklı sektörlerdeki uygulamalarını incelemektedir. Çeşitli sektörlerden vaka çalışmaları ve bu değerlendirmelerde kullanılan yöntemler analiz edilmiştir. Bulgular, inşaat ve enerji sektörlerinin LCSA yöntemini kullanan vaka çalışmalarının çoğunluğunu oluşturduğunu, ürün tasarımı sektörünün ise geride kaldığını göstermektedir. Ürünlerin sürdürülebilir tasarım hedeflerine ulaşılabilmesi için seri üretime geçmeden önce sürdürülebilirliğinin değerlendirilmesi kritik öneme sahiptir. Bu nedenle, ürün tasarımında LCSA kullanımının artırılması, sürdürülebilirlik hedeflerine ulaşmak için önemli bir adım olarak değerlendirilmektedir.

1. INTRODUCTION (GİRİŞ)

Sustainability, as defined by the Brundtland Report in 1987, is expressed as 'meeting the needs of the present generation without compromising the ability of future generations to meet their own needs' [1]. This concept has gained significant importance in the modern world and has been adopted in various sectors. However, the question of how to measure and evaluate sustainability has been a crucial research topic since the emergence of this concept. Life Cycle Assessment (LCA) is one of the leading methods for assessing the environmental impacts of products. LCA analyzes

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the environmental impacts of products throughout their entire life cycle, from raw material extraction to production, use, and final disposal [1].

To assess the economic dimension, Life Cycle Costing (LCC) and to analyze social impacts, Social Life Cycle Assessment (S-LCA) have been developed [2]. While these methods address different dimensions of sustainability, each alone does not provide a comprehensive evaluation. Life Cycle Sustainability Assessment (LCSA), however, offers a more holistic and comprehensive evaluation by considering these three dimensions (environmental, economic, and social) together [3].

LCSA is recognized as an important tool in sustainability assessments and is increasingly used in various sectors. This approach plays a critical role in achieving sustainability goals and offers a robust method for reducing the environmental impacts of products, increasing economic efficiency, and promoting social responsibility [4].

The purpose of this study is to examine the use of LCSA in the literature and to identify its applications in different sectors. Specifically, the performance of LCSA applications in the field of product design compared to other areas will be analyzed. In this context, the extent to which LCSA is used in product evaluations and the challenges encountered in this process will be addressed. The study emphasizes the need for more widespread use of LCSA in product design processes and highlights the importance of this method in achieving sustainability goals.

2. THEORETICAL FRAMEWORK (TEORİK ÇERÇEVE)

2.1. Life cycle sustainability assessment (Yaşam döngüsü sürdürülebilirlik değerlendirmesi)

Finkbeiner and colleagues (2010) highlight the multidimensional structure of LCSA and the holistic perspective it offers in sustainability analyses, defining LCSA as "an approach that integrates environmental, economic, and social life cycle assessment methods, aiming to obtain more comprehensive results by considering the three dimensions of sustainability together" [3]. Guinée and Heijungs (2011) describe LCSA as "a method that evaluates the environmental, economic, and social impacts of products and services throughout their entire life cycles," emphasizing the ability of LCSA to cover all stages of the life cycle [1]. Zamagni and colleagues (2013) define LCSA as "a way to evaluate the sustainability performance of a product or service by integrating environmental, economic, and social dimensions," and Kloepffer (2008) describes LCSA as "a method that offers a comprehensive and integrated analysis in sustainability assessments by combining LCA, LCC, and S-LCA" [4][5]. These definitions explain the fundamental components of LCSA and how these components are combined. To highlight the practical benefits of LCSA in achieving sustainability goals, Swarr and colleagues (2011) describe LCSA as "a holistic assessment method carried out throughout the entire life cycle of a product to reduce environmental impacts, increase economic efficiency, and promote social responsibility" [2].

In summary, LCSA is an approach that aims to obtain more holistic and comprehensive results in sustainability assessments by bringing together the environmental, economic, and social dimensions. The definitions and explanations of this method emphasize the multidimensional structure of LCSA, its ability to perform comprehensive analyses throughout the entire life cycle, and the holistic approach it offers in evaluating sustainability performance. Therefore, LCSA is recognized as a critical tool in achieving sustainability goals.

2.2. Sustainable product design (Sürdürülebilir ürün tasarımı)

Sustainable product design came to the forefront in the 1990s with the increase in environmental awareness and the global significance of issues such as climate change, resource scarcity, and waste management. Notable milestones emphasizing the importance of sustainable product design include the United Nations Conference on Environment and Development (Earth Summit) held in Rio de Janeiro in 1992 and the adoption of the Sustainable Development Goals (SDGs) in 2015 [5]. During this period, the demands of companies and consumers towards sustainability also increased. Consumers began to demand more environmentally friendly and ethical products, while companies turned to sustainable product design to gain a competitive advantage and comply with regulatory requirements [6]. Additionally, the Green Consumerism Movement and the concept of Circular Economy have further highlighted the importance of sustainable product design [7].

Sustainable product design is the process of designing products in accordance with environmental, economic, and social sustainability criteria. This approach aims to minimize the environmental impacts of products throughout their life cycles, ensure their economic sustainability, and make them socially fair and ethical [8]. Sustainable product design considers not only the performance of products during their usage phase but also the impacts of raw material extraction, production, distribution, use, and final disposal processes. Environmentally, it reduces resource use, minimizes waste and emissions, and contributes to the protection of ecosystems [9]. Economically, sustainable product design provides cost savings and supports long-term economic sustainability. More efficient production processes and innovative material uses can offer cost advantages to businesses [10]. Additionally, sustainable products can create market differentiation and competitive advantage, helping businesses strengthen their positions in the market [11]. Socially, sustainable products help companies fulfill their social responsibilities and offer consumers products that adhere to ethical values and fair trade principles [12].

Product design plays a critical role in achieving sustainability goals. Evaluating the environmental, economic, and social impacts of products throughout their life cycles is necessary for sustainable product design. However, findings in the literature show that the LCSA method is used less in the field of product design compared to other areas. This situation can negatively affect the sustainable product development process. Therefore, the use of LCSA in product design processes needs to be more widespread.

In summary, LCSA is an approach that aims to obtain more holistic and comprehensive results in sustainability assessments by bringing together the environmental, economic, and social dimensions. The definitions and explanations of this method emphasize the multidimensional structure of LCSA, its ability to perform comprehensive analyses throughout the entire life cycle, and the holistic approach it offers in evaluating sustainability performance. Therefore, LCSA is recognized as a critical tool in achieving sustainability goals.

3. METHODS (Yöntemler)

This review study was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, which aim to ensure the transparent, complete, and consistent reporting of systematic reviews. A comprehensive literature review was conducted to identify relevant studies on LCSA. The literature search was conducted in three well-established and widely recognized databases:

•**Web of Science:** A comprehensive, multidisciplinary platform known for its reliability and coverage of peer-reviewed research.

•**Scopus:** One of the largest abstract and citation databases for academic journal articles, covering a wide array of disciplines.

•**Emerald:** A specialized database focusing on management, sustainability, and related fields.

The databases were selected based on their reliability, extensive coverage of peer-reviewed research, and relevance to the scope of this study. The literature search included studies with case examples published in English and Turkish up to June 2024. Boolean search tools were used in the aforementioned databases with the search terms ("Life Cycle Sustainability Assessment" OR "Life Cycle Sustainability Analysis" OR "Life Cycle Sustainability A*" OR "LCSA"). As a result of the search, 342 relevant titles were found on Web of Science, 262 on Scopus, and 128 on Emerald. The studies obtained from the literature search were evaluated based on specific inclusion and exclusion criteria.

Inclusion Criteria:

•**Topic:** The studies had to focus on Life Cycle Sustainability Assessment (LCSA), encompassing its environmental, economic, and social dimensions.
•**Study Type:** Only case analysis studies were considered to ensure practical applicability.
•**Sector:** The selected studies needed to cover multiple sectors, including construction, energy, chemicals, product design, and others, providing a diverse view of LCSA applications.
•**Language:** The research focused on studies published in English and Turkish up until June 2024.

Exclusion Criteria:

•**Full Text Access:** Studies for which the full text was not accessible were excluded.
•**Languages:** Studies published in languages other than English and Turkish were omitted.

•**Out of Scope:** Studies not directly related to LCSA or evaluating only one dimension of sustainability (environmental, economic, or social).

The titles and abstracts of the articles identified from the literature search were screened and evaluated for relevance. The full texts of the eligible studies were reviewed, and data on the study's objectives, methods, findings, and conclusions were collected. The data collection process involved the following steps:

1. **Title and Abstract Screening:** The titles and abstracts of the studies were initially screened for eligibility.
2. **Full-Text Review:** The full texts of studies deemed suitable in the title and abstract screening were reviewed and evaluated according to the inclusion criteria.
3. **Data Extraction:** Data from the included studies were extracted after a detailed review, and content not fitting the scope was excluded. Duplicate studies found in all three databases were also removed at this stage.

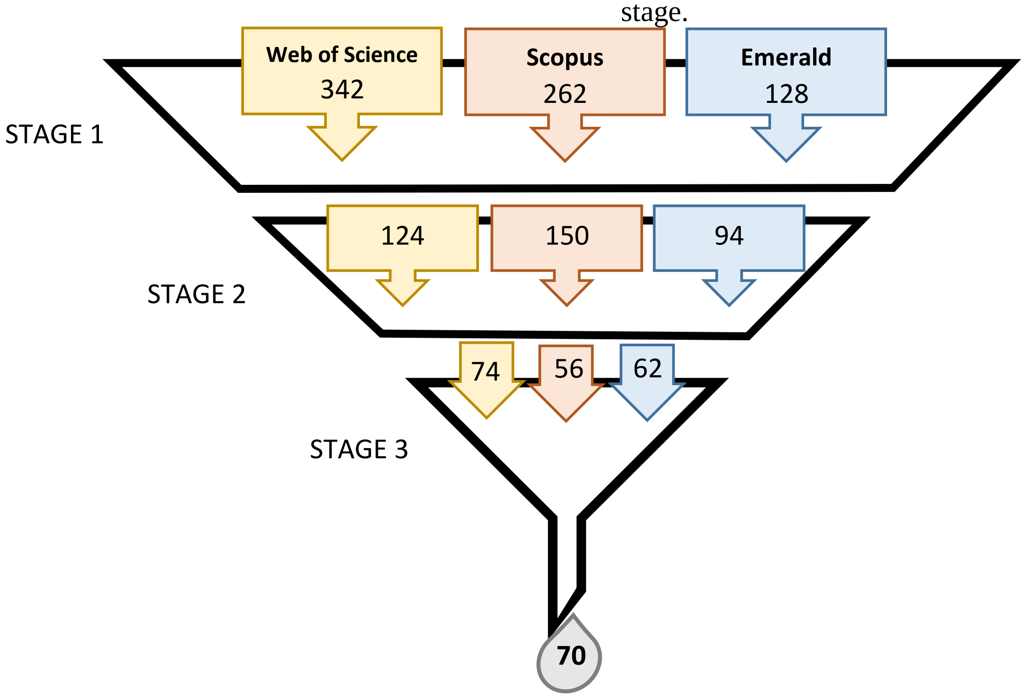


Figure 1. Schematic illustration of the data collection process (Veri toplama sürecinin şematik gösterimi)

The methodology used to determine the application rates of LCSA across sectors involved analyzing the number of case studies applying LCSA in specific sectors (e.g., construction, energy, chemicals, product design) over different time periods (2012–2007, 2018–2013, and 2024–2019). This was done by reviewing the frequency of LCSA usage reported in the case studies. Studies were categorized based on the sector they focused on, and the number of studies from each sector was compared across the three time periods.

The AMSTAR 2 checklist was used to assess the risk of bias in the studies. AMSTAR 2 is a tool for evaluating the methodological quality of systematic reviews, focusing on critical areas such as study design, data extraction, and analysis. Although originally developed for health interventions, its criteria are applicable to systematic reviews in other fields, ensuring reliability and validity.

This method, in accordance with the PRISMA 2020 protocol, ensured that the literature review on LCSA was conducted comprehensively and systematically. Consequently, comprehensive information was obtained on the position of LCSA in the literature, its use in different sectors, and its importance in product design.

4. FINDINGS (BULGULAR)

Following an initial literature review comprising a total of 368 studies, 94 studies meeting the criteria were selected for detailed examination. Seventy studies meeting the quality criteria were included and analyzed in this paper. These studies were conducted across various sectors, covering a broad spectrum of LCSA (Life Cycle Sustainability Assessment) application.

Table 1. LCSA Studies in the Construction Sector (Yapı Sektöründe LCSA Çalışmaları)

Author	Date	Approach	Method	Case Study
Vazquez-Lopez et al.[13]	2024	LCC	Construction Information Classification System (CICS)	Middle School Building Project
Ullah et al. [14]	2023	LCSA	Causal Loop Diagram (CLD)	Public Hospitals in Pakistan
Llatas et al. [15]	2022	LCSA	(Building Information Modelling) BIM, Dynamo Script	La María, a multi-family house located in Seville, Spain
Shadram and Mukkavaara [16]		LCC+LCE +LCCI	Multi-objective optimization	Apartment Building, Sweden
Filho et al. [17]		LCSA	BIM, Fuzzy Analytical Hierarchy Process (FAHP)	Material selection for low-income housing construction
Jena and Kaewunruen [18]	2021	LCA+LCC	-	FRP Composite Footbridge
Soust-Verdaguer et al. [19]		LCSA	BIM	La María, a multi-family house located in Seville, Spain
Tokede et al. [20]		LCSA	Integral Theory (IT)	Facade Design, Geelong, AustraliaAvustralya
Janjua et al. [21]		LCSA	Key Performance Indicators (KPI)	Typical Building in Western Australia
Ek et al. [22]	2020	LCA+LCC	Product Environmental Footprint (PEF)	Examination of Two Bridge Design Alternatives
Navarro et al. [23]		LCSA	Multi-Criteria Decision-Making Methods (MCDM)	Bridge Design
Vishnu and Padgett [24]		LCS	Probabilistic Life Cycle	MSSS Concrete Beam Bridge Design
Milani and Kripka [25]	2019	LCA	ReCiPe Endpoint Methodology	Bridge Design
Liu and Qian [26]		LCSA	AHP, Elimination and Choice Translating Reality (ELECTRE)	Comparison of Modular, Semi-Prefabricated and Traditional Building
Ostermeyer et al. [27]	2013	LCSA	Pareto Optimization	Residential Building Renovation

Table 1 summarizes the analyses and findings of various academic studies conducted in the construction sector. These studies frequently adopt the Life Cycle Sustainability Assessment (LCSA) approach, often integrating it with Building Information Modeling (BIM). Studies by Llatas et al. (2022), Soust-Verdaguer et al. (2021), and Liu and Qian (2019) demonstrate how BIM and LCSA methods are jointly used to conduct sustainability analyses of projects.

Additionally, Multi-Criteria Decision-Making (MCDM) methods and various original methods developed by authors are also commonly used. Navarro et al. (2020) utilized MCDM in their study. These methods effectively assess different criteria in construction projects and aid in making optimal decisions.

Some publications mention the LCSA method in their titles and abstracts but do not address all three main pillars of sustainability (economic, environmental, and social) comprehensively. For example, studies by Shadram and Mukkavaara (2022), Jena and Kaewunruen (2021), Ek et al. (2020), and Milani and Kripka (2019) often omit social sustainability from their assessments.

Case study examinations reveal that pre-production evaluations of building and bridge designs are conducted. For instance, Vazquez-Lopez et al. (2024) analyzed a middle school building project using the Cost Integrated Construction Scheduling (CICS) method. Similarly, Ullah et al. (2023) employed LEED and CLD methods in their study on public hospitals in Pakistan.

Moreover, Shadram and Mukkavaara's (2022) study on an apartment building in Sweden using a multi-objective optimization method highlights how sustainability analyses in the construction sector can be diversified through different methods. Filho et al. (2022) assessed sustainability by applying BIM-LCSA-FAHP methods for material selection in the construction of low-income housing.

These studies underscore the importance of diverse approaches and methods in conducting sustainability assessments in the construction sector, significantly contributing to both the design and construction processes of projects. However, a comprehensive consideration of all dimensions of sustainability is necessary for more balanced and thorough analyses.

Table 2. LCSA studies in the energy sector (Enerji sektöründe LCSA çalışmaları)

Author	Date	Approach	Method	Case Study
Gonzales-Calienes et al. [28]	2023	LCA+LCC	TEA	Lithium-Ion Battery Recycling
Toosi et al. [29]	2022	LCSA	Machine Learning	Electronic Lock System in an Apartment, Bagnolo, Italy
Bonilla-Alicea and Fu [30]		SLCA	Social Impact Assessment (SIA)	Rooftop Solar Panels
Santillan-Saldivar [31]	2020	LCA	GeoPolRisk Factors	Lithium-Ion Battery
Guarino et al. [32]		LCESA	Structural Law (CL), Exergy Analysis (EA)	Biomass Boiler Design
Moslehi and Reddy [33]	2019	LCSA	Sustainability Compass	Integrated Energy System in a University Campus
Mahbub et al. [34]	2018	LCSA	PROMETHEE	Oxymethylene Ether (OME) Production from Forest Biomass
Akber et al. [35]	2017	LCSA	Weighted Clustered Function Based on Díaz-Balteiro and Romero (2004)	Life Cycle Sustainability Assessment of the Electricity Sector in Pakistan
Atılgan and Azapagic [36]	2016	LCSA	MAVT	Turkish Electricity Sector
Onat et al. [37]		LCSA	Fuzzy TOPSIS Method	Evaluation of Charging Alternatives for Electric Vehicles
Stamford and Azapagic [38]	2014	LCA	CML	Sustainability Assessment of Alternative Electricity Sources in the UK
Nzila et al. [39]	2012	LCA+LCC	Multi-Criteria Sustainability Assessment Characterization	Biogas Production System in Kenya

Traverso et al. [40]		LCSA	Life Cycle Sustainability Dashboard	Sustainability of the Assembly Stage of Photovoltaic (PV) Module Production
Schau et al. [41]	2011	LCA+LCC	Life Cycle Sustainability Dashboard	Remanufacturing of Alternators
Zhou et al. [42]	2007	LCA+LCC	MCDM	Multi-Criteria Evaluation of Fuels

Table 2 details studies in the energy sector, demonstrating the diverse approaches and methods used in this field to assess sustainability. The energy sector, critical for sustainability evaluations, prominently features Life Cycle Sustainability Assessment (LCSA) and combinations of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC).

The energy sector draws attention as an important area in terms of sustainability assessments. As seen in Table 2, the most preferred approaches in the energy sector are Life Cycle Sustainability Analysis (LCA) and combinations of Life Cycle Analysis (LCA) and Life Cycle Costing (LCCC). These approaches are used to comprehensively assess the environmental, economic and social sustainability performance of energy projects.

Bonilla Alicea and Fu's (2022) study on the social impacts of rooftop solar panels assessed the social impacts of sustainable energy solutions using Social Life Cycle Analysis (SLCA) and Social Impact Analysis (SIA) methods. [30]. This study emphasises the importance of the social sustainability dimension in the energy sector and provides an important resource especially for the assessment of social impacts. In particular, a detailed consideration of social impacts can increase the social acceptance of sustainable energy projects and provide important information at the project planning stage.

Energy sector studies range from small-scale evaluations to extensive country-level assessments. For instance, Toosi et al. (2022) assessed the sustainability performance of an electronic lock system in an apartment in Bagnolo, Italy, using machine learning and LCSA. [29]. By examining the sustainability performance of a small-scale energy system, this study provides insights for optimising the environmental and economic impacts of individual projects.

On the other hand, comprehensive assessments in the energy sector examine the sustainability performance of country-level energy sectors. Akber et al. (2017) conducted a comprehensive life cycle sustainability assessment of Pakistan's electricity sector using the LCSA method [35]. Similarly, Atılgan and Azapagic (2016) evaluated Turkey's electricity sector using Multi-Attribute Value Theory (MAVT) and LCSA methods [36]. Nzila et al. (2012) analyzed the biogas production system in Kenya using multi-criteria sustainability assessment characterization and LCA+LCC methods [39].

The data in Table 2 illustrates the diversity and scope of sustainability assessments in the energy sector, from small-scale evaluations to large-scale national analyses. These studies highlight the applicability and effectiveness of various sustainability approaches and methods in improving the sustainability performance of energy projects, providing critical information for developing more effective energy strategies.

Table 3. LCSA studies in the chemical sector (Kimya sektöründe LCSA çalışmaları)

Author	Date	Approach	Method	Case Study
Mori et al. [43]	2023	LCSA	-	Production of Proton Exchange Membrane Fuel Cell (PEMFC) stack
Gosalvitr et al. [44]	2021	LCA+LCC	Modeling through Process Design and Flowchart (Aspen Plus V8.8)	Process improvement in cheese production
Pradhan et al. [45]		LCA	-	Valorization of waste rice bran oil and duck bones

Samaroo et al. [46]	2020	LCA+LCC	Planetary Boundaries Life Cycle Inventory Analysis (PB-LCIA)	Design of eco-park with BAU + urea + UAN + Mel + MeOH
Zhang et al. [47]		LCSA	Knowledge-based and heuristic methods	Composite bumper beam and lithium-ion battery
Aberilla et al. [48]		LCSA	VIKOR	Water and energy supply
Nieder-Heitmann et al. [49]	2019	LCSA	MCDM	Evaluation of sugarcane lignocellulosics
Botos et al. [50]		LCSA	-	Comparison of REACH and TSCA regulations
Ekener et al. [51]	2018	LCSA	MAVT	Biomass-based and fossil transportation fuels
Nguyen et al. [52]	2017	LCA+LCC	Development of Inclusive Impact Index	Sustainability assessment of non-edible vegetable oil-based biodiesel in Ha Long Bay, Vietnam
Wulf et al. [53]		LCSA	Normalization, Weighting, and Aggregation	Assessment of sustainable supply of rare earth metals for permanent magnet production
Kucukvar et al. [54]	2014	LCA+TBL	Weighting based on Stochastic Multi-Attribute Analysis (SMMA)	Road pavement
Schneider et al. [55]		LCA	Development of characterization methods	Evaluation of a portfolio of 17 metals
Kucukvar et al. [56]		LCA+TBL	Fuzzy MCDA Method incorporating TOPSIS	Comparison of hot mix and warm mix asphalt mixtures

The evaluations presented in Table 3 detail the variety of approaches and focal points in efforts to enhance sustainability within the chemical sector. The studies assess the environmental impact and resource efficiency of various applications in the industry, aiming to measure their effects on sustainability.

Studies in the chemical sector prominently feature LCSA (Life Cycle Sustainability Assessment) and LCA+LCC (Life Cycle Assessment and Life Cycle Costing) approaches. These methodologies are adopted to evaluate diverse strategies for enhancing sustainability and analyzing the environmental impacts of different applications. For example, Mori et al. (2023) evaluated the production of Proton Exchange Membrane Fuel Cell (PEMFC) stacks, examining the potential impacts of innovations in energy technologies on sustainability [43]. Such studies emphasize the potential for innovative energy solutions to improve environmental performance.

On the other hand, Gosalvitr et al. (2021) focused on process improvements in cheese production through process design and flowchart modeling, aiming to enhance the efficiency and reduce the environmental impacts of production processes [44]. These evaluations highlight the importance of improving the sustainability of manufacturing processes.

Another significant focus in the chemical sector is waste management and resource efficiency. Pradhan et al.'s (2021) evaluation of waste rice bran oil and duck bones reflects the pursuit of sustainable solutions in waste management [45]. Similarly, Zhang et al. (2021) assessed composite bumper beams and lithium-ion batteries using knowledge-based and innovative methods to enhance material sustainability [47].

Regulations and characterization play a crucial role in sustainability assessments. Botos et al. (2021) compared REACH and TSCA regulations to examine the impacts of chemical safety and environmental regulations on sustainability [50]. Furthermore, Schneider et al. (2014) developed characterization methods to evaluate a portfolio of 17 metals, assessing the influence of chemical regulations and material selections on sustainability [55].

In conclusion, evaluations in the chemical sector demonstrate the use of various sustainability strategies and methodologies. Topics such as environmental impact, waste management, energy efficiency, and regulatory compliance are central to research aimed at enhancing sustainability in the sector. This diversity supports a comprehensive approach to making chemical sector applications more environmentally friendly and economically efficient.

Table 4. LCSA studies in the environmental sector (Çevre sektöründe LCSA çalışmaları)

Author	Date	Approach	Method	Case Study
Song et al. [57]	2024	LCSA	MOO, H-LCA	Zhuzhou City
Opher et al. [58]	2018	LCSA	AHP	Sustainability of reclaimed domestic wastewater usage
Reddy et al. [59]		LCSA	Integrated Value Model for Sustainability Assessment (MIVES)	Examination of alternatives for cleaning contaminated lake sediments
Wang et al. [60]	2017	LCSA	Single-Objective Optimization	Waste Bank program in Bandung City, Indonesia
Sou et al. [61]	2016	LCSA	AHP	Reuse of bottom ash
Kalbar et al. [62]		LCA	TOPSIS	Technology selection for lake rejuvenation and housing projects
Foolmaun and Ramjeawon [63]	2013	LCSA	AHP	Disposal of PET bottles
Khalili et al. [64]		LCA	Multi-Criteria Decision Tool Based on Stakeholder Ratings	Waste management of cigarette butts in the tobacco industry

Table 4 illustrates the wide range of methods and diverse environmental issues addressed in studies conducted in the environmental sector. The examined studies highlight the prominence of LCSA (Life Cycle Sustainability Assessment) and LCA (Life Cycle Assessment) approaches in environmental management. Methods such as MOO (Multi-Objective Optimization), AHP (Analytic Hierarchy Process), MIVES (Integrated Value Model for Sustainability Assessment), and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) offer a broad spectrum of applications for evaluating environmental sustainability.

The use of these methods allows for comprehensive environmental impact assessments. For example, Song et al. (2024) evaluated the environmental sustainability of Zhuzhou City, while Opher et al. (2018) examined the sustainability of reclaimed domestic wastewater usage [57] [58]. These studies contribute to developing effective strategies for both local and global environmental issues.

The topics addressed in these studies include waste management, water and lake cleanliness, energy, and resource usage—key areas for enhancing environmental sustainability. For instance, Pradhan et al. (2021) evaluated technology selection for lake rejuvenation and housing projects, while Khalili et al. (2013) assessed the waste management of cigarette butts in the tobacco industry [45] [64]. These evaluations demonstrate how solutions are developed and applied to various environmental management problems.

Recycling and waste management play a critical role in reducing environmental impacts. Foolmaun and Ramjeawon (2013) addressed the disposal of PET bottles, while Khalili et al. (2013) focused on waste management of cigarette butts in the tobacco industry [63] [64]. Such analyses significantly contribute to the development of waste management and resource recycling strategies.

In conclusion, Table 4 showcases the diversity of studies in the environmental sector and the advantages of various methods used in these studies in terms of environmental sustainability. The studies provide a comprehensive examination of environmental impact and resource management, forming a solid foundation for developing sustainable environmental policies.

Table 5. LCSA studies in the various sectors (Çeşitli sektörlerde LCSA çalışmaları)

Sector	Author	Date	Approach	Method	Case Study
Logistics	Ren and Toniolo [65]	2018	LCSA	DEMATEL and EDAS	Ranking hydrogen production pathways
	Helbig et al. [66]	2016	LCSA	Development of characterization methods	Supply chain of polyacrylonitrile-based carbon fibers
	Ren et al. [67]	2015	LCSA	AHP and VIKOR	Evaluation of bioethanol production pathways in China
Automotive	Cimprich et al. [68]	2017	LCSA	Development of characterization methods	Comparison of electric and internal combustion engine vehicles
	Gemechu et al. [69]		LCSA	Assessment of geopolitical supply risks	Metals used in the life cycle of an electric vehicle
	Onat et al. [70]	2016	LCSA	Compromise Programming	Sustainability assessment of alternative passenger vehicles
Agriculture	De Luca et al. [71]	2018	LCSA	AHP	Cultivation of Calabria olives
	Zortea et al. [72]		LCSA	Life Cycle Sustainability Dashboard	Assessment of soybean production in Southern Brazil
	Aziz et al. [73]	2016	LCSA	Normalization and Weighting	Evaluation of composting systems for two types of compost products
Product	Lam et al. [74]	2021	LCSA	-	Wind turbine design
	Zanchi et al. [75]		LCSA	Fuzzy TOPSIS	Vehicle dashboard
	Ribeiro et al. [76]	2020	LCSA	-	Motorcycle lever and crank
	Feng and Huang [77]		LCSA	Topological Optimization, Bionic Method	Examination of machine tools
Services	Biedermann et al. [78]	2021	LCSA	-	Clothing boutique and exhibition layout
	Lopez et al. [79]	2020	LCSA	Foreground system (FS), Background system (BS)	Dairy production process and retail clothing

Materials	Raymond et al. [80]	2021	LCA	-	Comparison of five flooring materials
	Cimprich et al. [81]	2018	LCSA	Development of characterization methods	Material substitution for electric vehicles and dental X-ray systems
	Blundo et al. [82]	2019	LCSA	-	Evaluation of four main types of ceramic tiles produced in Italy
	Akhtar et al. [83]	2017	LCA+LCC	Analytic Hierarchy Process (AHP)	Material selection for sewer pipes

Table 5 comprehensively illustrates sustainability and assessment studies across different sectors, each employing distinct methodological approaches and evaluation techniques tailored to specific sectoral requirements.

Studies in the logistics sector generally focus on optimizing supply chains and processes. For example, Ren and Toniolo (2018) conducted a technical analysis ranking hydrogen production pathways, while Helbig et al. (2016) characterized the supply chain of polyacrylonitrile-based carbon fibers [65] [66]. Ren et al. (2015) evaluated bioethanol production pathways in China using AHP and VIKOR [67]. These studies aim to enhance the efficiency and minimize the environmental impact of logistics processes through decision-making and characterization methods.

In the automotive sector, Cimprich et al. (2017) compared electric and internal combustion engine vehicles to evaluate which technologies are superior in terms of sustainability [68]. Gemechu et al. (2017) analyzed the geopolitical supply risks of metals used in the life cycle of electric vehicles [69]. Onat et al. (2016) assessed the sustainability of alternative passenger vehicles using compromise programming [70]. These studies provide a broad range of analyses to improve the environmental and economic performance of automotive technologies.

Agricultural research uses various methods to enhance the sustainability of production processes. De Luca et al. (2018) evaluated the cultivation of Calabria olives, while Zortea et al. (2018) analyzed the life cycle sustainability of soybean production in Southern Brazil [71] [72]. Aziz et al. (2016) used normalization and weighting techniques to evaluate composting systems for different compost products [73]. These studies aim to increase the environmental efficiency and sustainability of agricultural production.

Studies in product design focus on developing innovative and sustainable products. Lam et al. (2021) evaluated wind turbine design, while Zanchi et al. (2021) used fuzzy TOPSIS to analyze vehicle dashboards [74] [75]. Ribeiro et al. (2020) examined motorcycle levers and cranks, and Feng and Huang (2020) investigated machine tools using topological optimization and bionic methods [76] [77]. These studies involve advanced techniques to improve the functional and environmental performance of product designs. The complexity and innovative approach of the methods used in product design shows that this field plays an important role in sustainability and performance improvement.

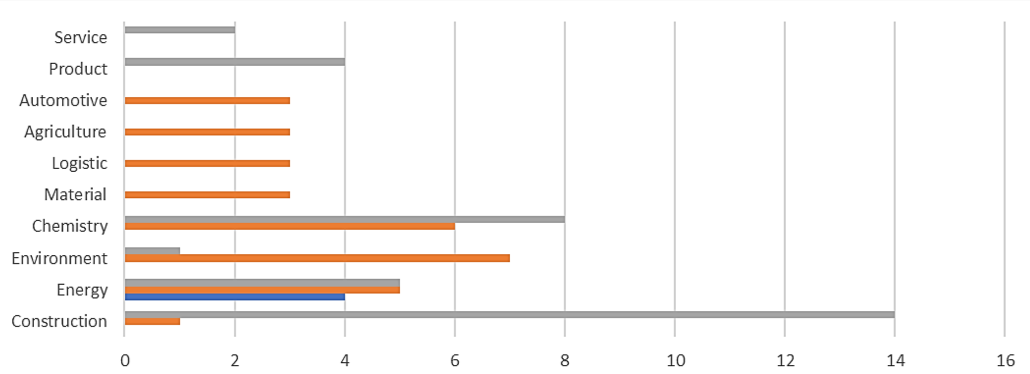
Research in services and materials science targets enhancing the efficiency of service processes and material selection. Biedermann et al. (2021) evaluated clothing boutiques and exhibition layouts, while Lopez et al. (2020) analyzed dairy production processes and retail clothing using foreground and background systems [78] [79]. In materials science, Raymond et al. (2021) compared five flooring materials, Cimprich et al. (2018) examined material substitution for electric vehicles and dental X-ray systems, and Blundo et al. (2019) evaluated ceramic tiles produced in Italy [80][81][82]. Akhtar et al. (2017) studied material selection for sewer pipes using AHP [83]. These studies enhance the efficiency and sustainability of service processes and material choices in various applications.

5. DISCUSSION (TARTIŞMA)

This study provides a detailed analysis of 70 academic works examining the application of Life Cycle Sustainability Assessment (LCSA) methods across various sectors. The findings indicate that LCSA is utilized in a wide range of fields, including construction, energy, chemistry, and others. In the construction sector, LCSA is frequently integrated with Building Information Modeling (BIM) for sustainability analyses. In the energy sector, LCSA is combined with methods such as Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) to comprehensively evaluate the environmental, economic, and social sustainability performance of projects. In the chemical sector, LCSA is integrated with LCA+LCC and unique methods to enhance process efficiency and reduce environmental impacts.

There are notable differences in the methods and case studies applied in each sector. While the LCSA method is actively used in the construction, energy, and chemical sectors, its application rate in the product design field is quite low. This highlights the importance of sustainability assessments during the product design phase. Studies related to product design generally focus on evaluating existing finished products. Such studies aim to analyze the sustainability performance of products post-production, without sufficiently emphasizing the importance of sustainability decisions made during the early stages of the design process. Applying the LCSA approach at the beginning of the product design process, before production, is crucial for ensuring the implementation of sustainable decisions. However, the low usage of LCSA in the product sector is noteworthy and indicates a gap in the application of sustainable design.

The provided data in the Figure 2. further elucidates the sectoral differences in the application of LCSA over three distinct periods (2012-2007, 2018-2013, and 2024-2019). For instance, in the construction sector, there has been a consistent increase in the number of studies applying LCSA, reaching 14 studies in the period from 2024 to 2019. This indicates a strong and growing commitment to integrating sustainability assessments within the construction industry. Similarly, the energy sector also shows a significant number of studies utilizing LCSA, particularly in the 2018-2013 and 2024-2019 periods, with 7 and 5 studies respectively



	Construction	Energy	Environment	Chemistry	Material	Logistic	Agriculture	Automotive	Product	Service
2019-2024	14	5	1	8	0	0	0	0	4	2
2013-2018	1	5	7	6	3	3	3	3	0	0
2007-2012	0	4	0	0	0	0	0	0	0	0

Figure 2. Frequency of LCSA Methods Application Across Various Sectors by Year (Yıllara göre çeşitli sektörlerde LCSA yöntemlerinin uygulanma sıklığı)

In contrast, the product design sector remains underrepresented in LCSA applications, with only 4 studies noted in the most recent period. This stark difference underscores the need for greater emphasis on sustainability in product design. There could be several reasons for the lower preference for the LCSA method in the product sector. One reason might be the much faster production process in the product sector compared to sectors like construction, energy, and automotive. Product designs require quick decision-making due to the faster pace of the process compared to designing a bridge, for example. Another reason could be that many products in the sector have shorter lifespans or are intended to have shorter lifespans. Unfortunately, the product sector, aligned with capitalism, supports rapid consumption and repeat purchases. Sustainable solutions, which would extend the product lifespan, are often met with resistance by firms. At this point, industrial collaborations and incentives can be used to provide companies with education and consultancy services, explaining the benefits of sustainable design from the perspectives of reducing production costs, improving quality, reducing waste, selecting appropriate materials, and aligning with customer preferences.

Other sectors, such as chemicals and materials, also demonstrate substantial engagement with LCSA, as evidenced by the high number of studies (8 for materials and 8 for chemicals in the 2024-2019 period). The logistics, agriculture, and automotive sectors show moderate engagement with LCSA, but they lag behind the leading sectors. For example, the logistics sector has seen an increase from 0 studies in the 2012-2007 period to 1 in the 2018-2013 period and 3 in the 2024-2019 period. Similarly, the automotive sector, which is crucial for addressing environmental impacts, shows incremental growth but remains limited in the number of studies.The service sector also appears to be gradually adopting LCSA, with 2 studies in the most recent period. This suggests an emerging recognition of the importance of sustainability in service-oriented industries.

Despite the demonstrated benefits of Life Cycle Sustainability Assessment (LCSA) across various sectors, its application in product design remains significantly underrepresented, and several key barriers contribute to this low adoption rate. One major challenge is the fast-paced nature of the product development process. Unlike industries such as construction or energy, where projects have longer timelines, product design cycles require rapid decision-making. This urgency often conflicts with the thorough and time-consuming analyses that LCSA entails, leading companies to prioritize short-term gains and quicker time-to-market over comprehensive sustainability assessments.

Another key factor is the short lifespan of many products in the design sector, which is often dictated by market demand for rapid consumption and frequent product turnover. In capitalist economies, where fast consumption is encouraged, extending the product lifecycle through sustainable design may seem counterproductive for firms reliant on repeated purchases. This creates a disincentive to adopt sustainability frameworks like LCSA that would prolong product use and reduce waste.

Additionally, cost and resource constraints pose a significant barrier to the implementation of LCSA at the early stages of product design. Performing LCSA requires specialized expertise, tools, and time, which may strain the resources of companies, particularly smaller firms. The costs associated with subscription-based LCSA tools, such as PSILCA and SHDB for Social Life Cycle Assessment (S-LCA), further deter widespread adoption. Companies may view the financial burden of integrating such tools as prohibitive, especially when the perceived immediate return on investment is unclear.

Moreover, there is a lack of awareness and expertise within many companies regarding the long-term benefits of sustainable product design. Many firms are unaware that implementing LCSA could ultimately lead to reduced production costs, improved product quality, and increased consumer preference for sustainable products. The limited internal expertise to conduct LCSA further compounds this challenge, as companies may not have the in-house capabilities to undertake such assessments effectively.

Overall, this study highlights the critical need for future research and policy interventions to promote the broader adoption of LCSA, particularly in the product design sector. By integrating LCSA early in the design process, industries can improve the sustainability performance of their products and processes, reduce production costs, improve quality, minimize waste, select appropriate materials, and better meet customer preferences. Additionally, strategies to overcome barriers such as cost and time constraints should be explored to facilitate the wider implementation of LCSA across all sectors.

6. CONCLUSION (SONUÇ)

This study provides a comprehensive analysis of the application of Life Cycle Sustainability Assessment (LCSA) methods across various sectors, highlighting significant disparities in adoption. While LCSA is actively utilized in sectors like construction, energy, and chemicals, its application in the product design sector remains notably low. This discrepancy underscores the need for greater emphasis on integrating sustainability assessments during the early stages of product design, which is crucial for making sustainable decisions.

The findings indicate that in sectors such as construction and energy, LCSA is often integrated with methods like Building Information Modeling (BIM) and Life Cycle Costing (LCC) to evaluate sustainability performance comprehensively. However, in the product design sector, studies tend to focus on evaluating existing products post-production, neglecting the importance of early-stage sustainability decisions. The rapid production processes and shorter product lifespans in this sector, driven by a capitalist market that favors rapid consumption, contribute to this gap.

The data further reveal that other sectors, such as chemicals and materials, show substantial engagement with LCSA, while logistics, agriculture, and automotive sectors exhibit moderate but growing adoption. The service sector is also gradually recognizing the importance of sustainability, as indicated by the recent increase in LCSA applications.

In conclusion, the analysis highlights significant disparities in the adoption of LCSA across different sectors. While some sectors, such as construction, energy, and chemicals, demonstrate robust engagement with LCSA, others, notably the product design sector, show limited application. This gap presents a critical opportunity for future research and policy interventions aimed at promoting LCSA in underrepresented sectors. Emphasizing the integration of LCSA early in the design process can foster sustainable decision-making and improve the overall sustainability performance of products and processes across industries.

DECLARATION OF ETHICAL STANDARDS
(ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Seher DEMİR*:** She conducted the literature review, analyzed the results, and carried out the writing process of the paper.

Literatür taraması yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

***Veysel ÖZDEMİR*:** He provided guidance and contributed to the planning and direction of the research.

He provided guidance in the planning and steering of the research

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

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