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Development of a Global Framework for an Integrated Life Cycle Assessment (LCA) Model in Quality, Safety and Environmental (QSE) Management Systems: Improving Environmental, Social and Economic Sustainability Performance

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Abstract: A framework to include life cycle assessment (LCA) in the importance assessment of quality, safety and environmental (QSE) aspects of a management system has been studied to improve the sustainable development performance in the environmental, social and economic dimensions. But there is a literature gap where impact assessment is a critical factor. This research follows a mixed-methods approach, including a survey of 127 Moroccan companies to assess the adoption and impact of LCA integration. The survey's findings show that 40% of companies have integrated LCA through significant advances in operational quality, regulatory compliance and sustainability performance. The findings also demonstrate how integration has enhanced long-term strategic decision-making, process optimization and environmental impact assessment. The proposed model aligns the requirements of sustainable LCA standards (ISO 14040/44, ISO 26000 and ISO 15686-5) with certifiable standards (ISO 14001, ISO 9001 and ISO 45001), addresses the opportunities and limitations of organizations during integration, and includes indicators for sustainability analysis. The study highlights how implementing LCA in QSE management creates a systematic approach to sustainability, particularly in terms of employee training, regular performance monitoring and regulatory compliance. In light of changing laws and industry norms, these findings provide a means for sectors to enhance their sustainability performance.

Keywords: LCSA; LCC; environment; sustainability impact; regulatory; social life cycle

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1. Introduction

Life cycle assessment (LCA) and quality, security and environment (QSE) management systems are among the most important industrial and environmental strategies, with a strong focus on sustainability. Many countries, including Morocco, are increasingly prioritizing environmental regulations that encourage companies to adopt LCA in order to assess the environmental impacts of products and production processes throughout their entire life cycle [1]. Today's Moroccan government aims to support major international efforts like the Paris Agreement 2016 [2], showing the country's commitment to sustainability and climate activities. Moroccan companies have integrated environmental management practices for both local and international purposes. For instance, some manufacturing sectors in Morocco have started applying environmental performance measures to their

QSE management systems, recognizing the need to balance operational excellence with sustainable practices.

LCA is a principal tool for sustainable development management. It assesses the product's environmental impact—its stages from cradle to grave [1]. We use LCA in the field of environmental management [3] to evaluate the total environmental impacts of different products and systems from raw material extraction (mining) to production, use and final disposal or recycling. The scope definition and the inventory analysis are mandatory according to ISO 14040-14044 [4,5]. The impact assessment and interpretation require additional steps that are not generally considered. LCA is used in different contexts, including Environmental Product Declarations, to provide clear information about the product life cycle [6], to help inform policy- and decision-making in business [7] and to help organizations comply with green procurement and other policies such as greenhouse gas (GHG) emission reporting as part of corporate sustainability planning.

Meanwhile, conventional LCA has limitations, especially its lack of a structured approach to the social and economic aspects. To achieve these gaps, the life cycle sustainability assessment (LCSA) was presented as an expanded approach. With regard to the social framework, and in contrast to traditional LCA, the discussion on integrating social aspects into LCA began in the 1990s [8]. This led to the development of the life cycle sustainability assessment (LCSA), which incorporates social and economic dimensions, aspects that have increasingly attracted the attention of industries in recent years, especially in the context of sustainable development [9–12]. The concept of LCSA is developed to overcome the limitations of traditional LCA [13], which, though successful in the assessment of environmental impacts, is often neglected [14]. This extended framework is expected to afford a wider scope of product or system sustainability assessment [13,15,16] and thus provide more meaningful outputs to concerned decision-makers in policy or corporate settings [13,17,18]. The background of LCSA can be traced to the early 2000s, when scholars and experts realized that environmental sustainability would not help bring sustainable development [19]. In this regard, pioneering works, for instance, by Kloepffer (2008) [20], suggested the integration of Life Cycle Costing (LCC) and social life cycle assessment (S-LCA) into the conventional LCA framework. And he defines LCSA as the sum of LCA, LCC and S-LCA: "LCSA = LCA + LCC + S-LCA". The incorporation of all three elements lets LCSA deliver an all-inclusive assessment that finds great use in strategic decision-making [9] and policy-making [9,10].

However, the complexity of LCSA in data and methodological challenges hinders its wide application. The problems with LCSA implementation are many, starting from the assessment, which is becoming more complicated. Therefore, data collection is increasing and represents a major challenge, as it is still difficult to obtain accurate and consistent information on economic costs, working conditions and environmental footprints [21]; determine system boundaries; choose effect categories; and guarantee methodological consistency across several sustainability indicators, which are all part of the more complicated LCSA evaluation procedure [19] and are more complicated than conventional LCA. Furthermore, the lack of widely recognized approaches for LCC and S-LCA makes benchmarking and regulatory alignment more difficult [22]. Making decisions is further made more difficult by the necessity to balance trade-offs between sustainable aspects [23]. Since these obstacles prevent LCSA from being widely used, its incorporation into structured management systems is required to improve usability.

Multiple types of LCA integration models have been proposed; each has particular strengths and weaknesses, including regulatory compliance, stakeholder engagement and comprehensive assessments. But there are still significant barriers, including standardization issues and finding an agreement between social and economic factors. A summary of

these models' benefits, limitations and uses is provided in Table 1, which also highlights the gaps that must be filled for a more successful LCA-QSE integration.

Table 1. Critical review of LCA/LCSA and management systems.

Model/Approach	Advantages	Limitations	Standards Used	Application Context
Integration of footprints (water and carbon) [24]	Identify gaps in the environmental performance of organizations	LCA had no significant effect on company performance	ISO 14001 [25]	EMS in Malaysian companies
Social Organizational LCA (SOLCA) [12]	Holistic assessment of social and environmental risks across supply chains	Difficult to apply in the different departments of the company	SLCA, O-LCA (SOLCA)	Management of social and environmental risks across supply chains
Sustainability and the life cycle approach: Product-oriented environmental management (POEMS) [26]	* These systems enable a holistic approach to be taken to managing environmental impacts * Collaboration with stakeholders	Reticence about the global life cycle management initiative due to a lack of incentives or a focus on their own production processes	ISO 14001, ISO 9001 [27], OHSAS 18001 [28], EMAS [29]	Danfoss Group (Integration of LCA and EMS)
Integration of LCSA into Circular Economy (CE) in company Management System MS [30]	Supporting long-term sustainability planning	Data collection and the lack of standardized methodologies for assessing social impacts in the context of CE	ISO 14040	Industries in transition to CE models (construction and manufacturing)
Integration of LCA into EMS [7,31,32]	* By using LCA and these detailed data, organizations have aligned themselves with sustainability objectives and improved their EMS * Integration supported organizations to achieve better compliance with the requirements of ISO 14001:2015, particularly in the areas of the life cycle perspective and environmental performance evaluation * LCA data supported continual improvement initiatives within the EMS, ensuring that environmental impacts were assessed and minimized	* The challenges associated with resource limitations, particularly in SMEs, where implementing LCA is more difficult * The difficulty for organizations to fully integrate LCA into the EMS in view of the complexity of collecting and assessing life cycle data	ISO 14001, ISO 14040	Various industrial sectors (manufacturing and energy industries, production chains)
EMS and LCA at the local level [33]	Efficiently assessing environmental impacts	Measuring indirect impacts is complex and standardization lacks coherency	ISO 14001, EMAS	EMS of public administrations

Table 1. *Cont.*

Model/Approach	Advantages	Limitations	Standards Used	Application Context
Integrating LCA into QMS [34]	* Optimizing the use of resources to improve product life cycle performance and reduce waste * Encouraging a sustainability approach by promoting alignment between quality and environmental objectives	* Need for training and significant resources for employees to understand and apply LCA principles as part of quality management * There has been limited exploration of how social aspects can be integrated with quality and environmental aspects	ISO 9001, ISO 14040	Manufacturing industries (automotive and electronics sectors)
Integrates Quality indicators and LCA [35,36]	* Comprehensive decision support * Forward-looking product development * Flexibility to tailor the decision-making process * Sensitivity analysis	* Integration may require significant resources * Availability of data * Complexity of determining the appropriate weighting between quality and environmental impact	ISO 9001, ISO 14040/44	Applied in manufacturing industries
Integrates Environmentally Conscious Quality Function Deployment (ECQFD), LCA, sustainable and environmental analysis [37,38]	* Integration of customer requirements, environmental impacts and sustainability measures in a single model * Facilitates decision-making * Eco-innovation * Life cycle focus * Improved decision-making	* Collecting data for LCA and customer feedback is time-consuming and can limit the speed of implementation * Data dependency * Integration requires considerable expertise and may require significant resources * Integrating Q & E assessments into a unified framework may require significant resources	ISO 9001, ISO 14040	Applied in mechanical engineering and product design

To address these challenges, the integration of LCA into management systems provides the opportunity for organizations to reach a full sustainability approach [31,32,39] and minimizes environmental impacts while guaranteeing the activities' quality and safety. The management systems of QSE in the realm of industrial operations contribute to enabling sustainable industrial operations [40,41]. These systems fall under established ISO standards that are recognized and internationally standardized and provide "specification with guidance for use that depend upon specific organizations"; however, they seek to address quality management, environmental management, and occupational health and safety management, which are all future frameworks [42]. The LCA integration within management systems offers a range of processes of compliance and optimization [34] for environmental and operational efficiency [43]. It is particularly relevant because of the pathways to regulatory pressures [31], market demands for sustainability and continuous improvement [44,45]. This integration demonstrates a major change in how organizations carry out their activities in sustainability and operational excellence. In the past few decades, LCA has gone from being an emerging environmental assessment tool to an integral part of wide-reaching QSE strategy [46].

We divided this development into three basic stages:

- Early development from the 1990s to the early 2000s;
- Seed awareness and initial integration from the mid-2000s to the 2010s;
- Mainstream acceptance with progressive integration beginning by 2020.

Each of these stages, serving as a platform for the following one, highlights major developments that paved today's LCA integration scene, driven by regulatory pressures [31,47], technological improvements [1,48] and a rising corporate sustainability focus [1,7,49]. Figure 1 provides an overview of these stages that helped to thicken the incorporation of LCA into QSE management systems.

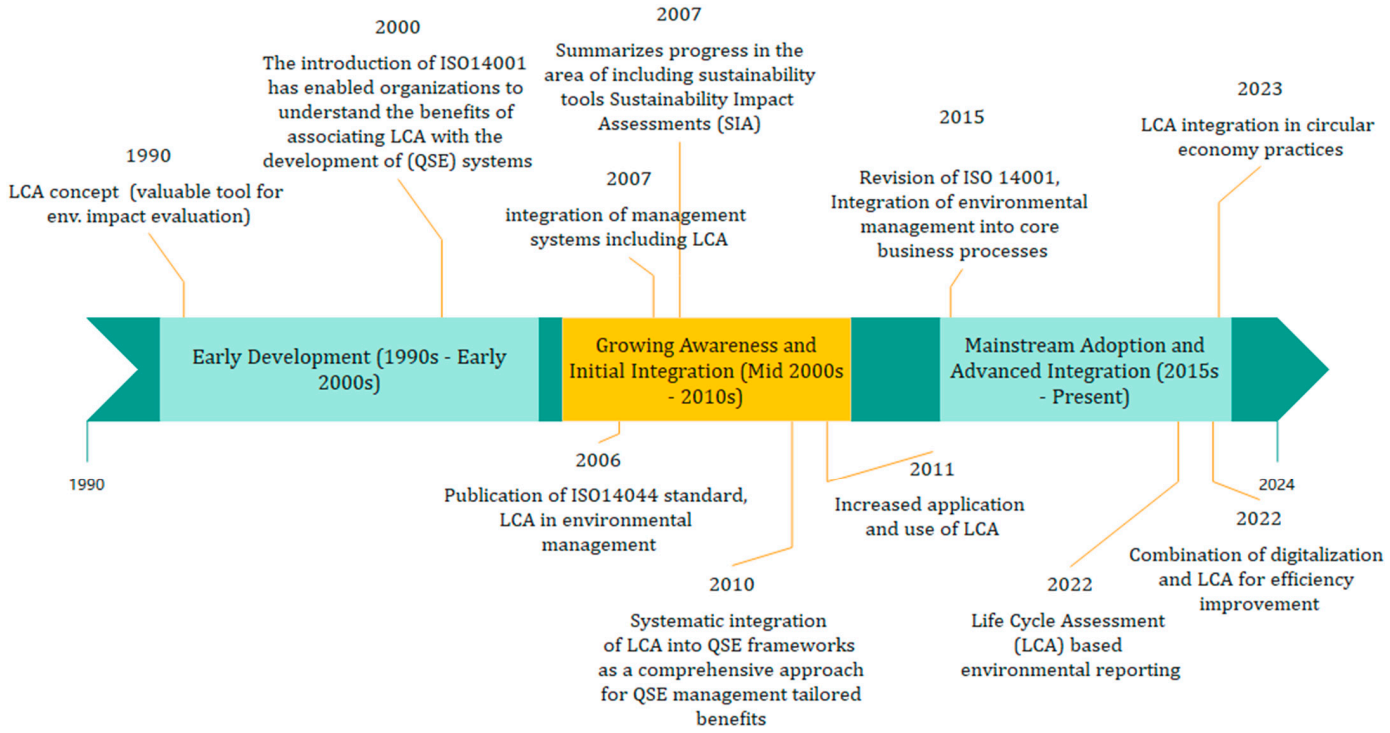


Figure 1. The development of LCA integration in QSE systems from early development to curly integration [25,43,44,50–57].

Even though sustainability issues are becoming more widely acknowledged, there is still fragmentation in the way LCA is incorporated into QSE management. Performance measurement, regulatory alignment, and operational efficiency are among the challenges that many companies face when trying to integrate LCA approaches with ISO-based QSE frameworks. As Sala et al. (2020) [58] emphasize, LCA provides comprehensive information on global environmental impacts and resource limitations, which helps improve environmental management systems; however, its integration into SMS remains underexplored. Additionally, few studies have correctly addressed the involvement of stakeholders and their requirements [59], and there are more specific areas where a dearth of research exists, such as performance measurement [60,61]. These gaps reveal the necessity of a comprehensive integrated framework of all QSE management components to improve systems' performance and durability [30,43].

In order to address the current research gaps, this article offers an organized framework that leads firms through a methodical process to improve operational excellence, sustainability performance, and regulatory compliance. This article is structured as follows: The Methodology section outlines the research approach, including survey analysis and interviews with experts that inform the development of the integrated LCA-QSE

model. Subsequently, the proposed model is designed to align with international standards (ISO 14001, ISO 9001 and ISO 45001), ensuring a comprehensive product evaluation approach that considers the organization's environmental, social and economic impacts and describing the key components and performance indicators. Finally, the Discussion and Conclusions sections highlight the broader implications of this integration and offer recommendations for practitioners, suggesting directions for future research. This paper aims to contribute to the body of knowledge by providing a clear and actionable model to support the integration of sustainability into QSE systems.

2. Methodology

The first objective of this study is to explore, within organizations and manufacturing industries, the positive impact and obstacles of integrating the LCA tool into QSE management systems. The second purpose is to identify the correlation points and independence between QSE systems and the LCA tool from an operational perspective (improving process efficiency, resource optimization and decision-making) and a regulatory perspective (through ensuring compliance with environmental laws, sustainability standards and regulatory requirements to the benefit of the implementation of the LCA-QSE integration model). The study also identifies the criteria for successful integration, as well as the shortcomings and limitations observed in manufacturing companies. In light of these findings, this research work proposes a detailed integration model that outlines key stages, performance indicators, and regulatory requirements to be pursued with the intention of successfully integrating LCA within QSE management systems.

2.1. Data Validation

Before proceeding with data collection, it is essential to establish content validity to support the rationality of the survey, in particular for the purpose of research [62,63]. Therefore, a content validation form has been set up online to ensure that the panel of experts will have clear and specific expectations and insights. Interviews were conducted with researchers in quality management systems; environmental management lecturers; auditors and experts in certification organizations (ISO 14040, ISO 14040/14044, 9001 and 45001); and health, safety and environmental managers in the private sector. The evaluation scale used is as follows [64]:

1 = The item is not relevant to the measured domain;
2 = The item is somewhat relevant to the measured domain;
3 = The item is quite relevant to the measured domain;
4 = The item is highly relevant to the measured domain.

The data validity index was used to analyze the Item-level Content Validity Index (I-CVI) item for the overall Scale-level Content Validity Index (S-CVI) scale for all sections. After in-depth evaluation by six experts, the five parts of the questionnaire recorded a validity index of 0.92. According to Lynn [65], an I-CVI of at least 0.83 is considered acceptable. In other words, and on the basis of the experts' assessments and the CVI indices calculated, the questionnaire items are considered rational in terms of content, which validates their relevance for assessing the integration of LCA into QSE management systems. Table 2 shows the item and content validity index in detail.

Table 2. Relevance ratings on the item scale by six experts.

Item	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	I-CVI	*UA
Q 1.0: Company name: (optional)	3	3	4	2	3	3	0.83	0
Q 1.1: Your company is (Legal_form)	3	2	4	4	3	3	0.83	0
Q 1.2: Your company is in the sector	4	4	4	4	4	4	1.00	1
Q 1.3: Sector of activity	3	3	4	3	3	3	0.83	0
Q 1.4: Role of the respondent in the company?	3	3	3	3	3	3	1.00	1
Q 1.5: Size of company: (number of employees)	3	3	4	4	3	4	1.00	1
Q 2.0: Does your organization have a Management System?	3	4	4	3	4	4	1.00	1
Q 2.1: Does your organization have ISO certification?	3	4	3	3	4	3	0.83	0
Q 2.2: If yes, which standard?	3	3	4	3	4	3	0.83	0
Q 2.3: Are you interested in the Life Cycle concept of your products?	3	4	4	3	4	3	1.00	1
Q 2.4: If so, in which context?	3	3	4	3	3	3	0.83	0
Q 2.5: How management systems make your work easier (Benefits)	3	3	3	3	3	3	1.00	1
Q 2.6: How do you evaluate the efficiency of your management system?	3	4	4	3	4	4	1.00	1
Q 2.7: How do you identify opportunities for improvement within your QSE management system?	3	4	3	3	4	4	0.83	0
Q 2.8: How do you monitor and measure the efficiency of your system's improvement actions?	3	3	4	3	3	3	0.83	0
Q 3.0: Has your company assessed the life cycle (stages or phases) of its processes, procedures, products and/or services?	3	4	4	3	4	3	1.00	1
Q 3.1: if so, describe how	3	4	4	3	4	3	0.83	0
Q 3.2: In which extent are environmental indicators linked to LCA included in your MS?	3	4	4	3	4	4	1.00	1
Q 3.3: What is your perception of the relevance of LCA for QSE management systems?	3	3	4	3	3	3	0.83	0
Q 3.4: Do you work with suppliers, customers or other stakeholders to assess the environmental risks of your products/services?	3	3	4	3	4	4	0.83	0
Q 3.5: How do you measure environmental aspects and impacts within your company?	3	4	4	3	4	3	1.00	1
Q 3.6: Do you have indicators to measure, monitor and analyse the life cycle of your products/services?	3	4	4	3	4	4	1.00	1
Q 3.7: If yes, please specify	3	3	4	3	3	3	0.83	0
Q 3.8: How do you study the life cycle of your products/services?	3	4	4	3	4	3	1.00	1

Table 2. *Cont.*

Item	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	I-CVI	*UA	
Q 4.0: Do you assess the impact of your products on the environment?	3	4	4	3	3	3	0.83	0	
Q 4.1: Do you use software to assess the environmental impact of your products?	3	4	3	3	4	3	0.83	0	
Q 4.2: If yes, please specify?	3	3	4	3	3	3	0.83	0	
Q 4.3: Do you have a procedure for conducting an LCA?	3	4	4	3	4	3	1.00	1	
Q 4.4: Does your QMS or EMS or your MS in general encourage the carrying out of a life cycle analysis or feedback on this analysis?	3	4	4	3	4	4	1.00	1	
Q 4.5: Does your management system include LCA?	3	4	4	3	4	4	1.00	1	
Q 4.6: What benefits has your company gained from integrating LCA into its QSE systems?	3	4	4	3	4	3	1.00	1	
Q 4.7: What are the main barriers to integrating LCA into your QSE management systems?	3	4	4	3	4	4	1.00	1	
Q 5.0: How do you expect the LCA tool to evolve in your QSE systems?	3	4	4	3	4	3	1.00	1	
Q 5.1: What suggestions do you have for better integration of the LCA tool into QSE management systems?	3	4	4	3	4	4	1.00	1	
Q 5.2: What kind of training or development do you suggest for your company to better integrate LCA into QSE systems?	3	4	4	3	4	4	1.00	1	
							0.927		S-CVI/*Ave
Prop.Relev	0.943	0.971	1.00	0.857	1.00	0.971		**0.57**	S-CVI/*UA

UA: Universal Agreement, Ave: Average.

The proportion of relevance scores for experts [62,63,65] suggests that the items in the questionnaire are considered relevant for assessing the integration of LCA into QSE management systems.

2.2. Survey Development

To allow coherent integration into the management systems of QSE and LCA, it was important, in our study, to define performance expectations about the environment that we were seeking from the respondents. Thus, to advance this research on the integration of MS and LCA in Morocco, a study was conducted from February to August 2024, based on a survey distributed to various manufacturing industries. The survey was conducted among supervisors, quality management system managers, QSE/QHSE managers and R&D managers. This targeted approach not only provided comprehensive data on the integration of LCA into QSE Management Systems (QSE-MSs) but also yielded an integrated perspective on how LCA can align with companies' broader QSE objectives. Furthermore, the respondents' expertise and skills in the field will allow for a thorough understanding of the challenges and opportunities related to this integration. The survey was distributed to 402 Moroccan manufacturing organizations across various sizes and sectors, resulting in 127 responses, which represent 31.59% of the target population. Respondents highlighted

the necessity of comprehensive training and the inclusion of LCA principles in decision-making processes by integrating QSE management systems and LCA frameworks. The survey covered five topics: (1) company profile information, (2) overview of QSE management systems, (3) LCA practices, (4) integration of LCA and QSE, and (5) recommendations. The questionnaire was administered across various companies in different sectors. These survey settings were across different ranges of industries like construction, the automotive industry, the food industry sector, the clothing and textile industries and the aeronautics sector. The participants were predominantly from private sector companies.

2.3. Normative Framework and Correlation Tables

To clarify the correspondences between QSE and LCA management systems from a normative perspective, we first established the alignment between the requirements of ISO 9001, ISO 45001 and ISO 14001, following the chapter structure of ISO 9001:2015, ISO 14001:2015 and ISO 45001:2018, as outlined in 'Figure A1'. We then compared these with the criteria and frameworks of ISO 14040/14044, ISO 26000 [66] and ISO 15686-5 [67]. This approach enables a bidirectional understanding of their normative interdependencies and allows for the full integration of QSE management practices within the LCA framework. The study's system limits are defined in line with the methodological framework shown in Table 3, specifically according to ISO 14040/44 requirements for LCA. Using a cradle-to-grave methodology, this study evaluates every stage of the life cycle, including raw material extraction, manufacture, distribution, usage, and end-of-life management. The intersection of cost estimates (ISO 15686-5) and performance evaluation (ISO 9001, ISO 14001) means that sustainability impacts are evaluated over the whole life cycle of products and services, including their potential for recycling and disposal and beyond the company's operating boundaries. This approach not only guarantees compliance with internationally recognized standards but also makes our methodology more robust and reliable.

Table 3. Alignment between the clauses of QSE standards (High-Level Structure HLS) and the clauses of sustainability standards (ISO 14040/44, ISO 26000 and ISO 15686-5).

Requirements				
ISO 14040/44	**ISO 26000**	**ISO 15686-5**	**ISO 9001.15 ISO 14001.15 ISO 45001.18**	**HLS**
4. Methodological framework for LCA studies: ➪ 4.2. Goal and Scope Definition	6.Guidance on social responsability core subjects: ➪ 6.2. Organizational governance ➪ 6.8. community involvement and development	4. Principles of life cycle costing: ➪ 4.1. Purpose and scope of life cycle costing	➪ 4. Context of the Organization	*P
C. QSE 5. Leadership and commitment to implementing LCA guidelines and defining responsibilities for LCA activities				
4. Methodological framework for LCA studies: ➪ 4.3. Life Cycle Inventory Analysis	5. Recognizing social responsibility and engaging stakeholders: ➪ 5.3. Stakeholder identification and engagement	4. Principles of life cycle costing: ➪ 4.3. Typical analysis at different stages of the life cycle	➪ 6. Planning for the QSE-MS-	*P

Table 3. *Cont.*

Requirements				
ISO 14040/44	**ISO 26000**	**ISO 15686-5**	**ISO 9001.15 ISO 14001.15 ISO 45001.18**	**HLS**
4. Methodological framework for LCA studies: ➪ 4.4. Life Cycle Impact Assessment	6.Guidance on social responsability core subjects: ➪ 6.3. Human rights ➪ 6.5. The environment	4. Principles of life cycle costing: ➪ 4.6. Cost variables ➪ 6. WLC variables used in some investment appraisals ➪ 6.2. Externalities ➪ 6.3. Costs related to environmental impacts ➪ 6.4. Social costs and benefits	9. Performance Evaluation ➪ 9.1. Monitoring, measurement, analysis and evaluation	*C
4. Methodological framework for LCA studies: ➪ 4.5. Interpretation	7. Guidance on integrating social responsibility throughout an organization ➪ 7.3. Understanding the social responsibility of an organization	8. Uncertainty and risks ➪ 8.4. Sensitivity analysis and modeling of the effects of changing keys	10. Improvement actions ➪ 10.3 Continual Improvement	*A
5. Communication: ➪ 5.2. Documentation	7. Guidance on integrating social responsibility throughout an organization ➪ 7.5. Communication on social responsibility	9 Reporting ➪ 9.1. LCC analysis- Presenting the results and supporting information	7. Support and Resource management ➪ 7.5. Documented Information	*D
C. QSE 8. Integration of LCA activities process according to the phases outlined in ISO 14040/44 as part of the broader management system operations				
➪ 6. Critical Review	7. Guidance on integrating social responsibility throughout an organization ➪ 7.6. Enhancing credibility regarding social responsibility	4. Principles of life cycle costing: ➪ 4.10. Reporting LCC analysis 9 Reporting ➪ 9.3. Approvals and audit trail	9. Performance Evaluation ➪ 9.2. Internal Audits ➪ 9.3. Management Review	*C

P: Plan. D: Do. C: Check. A: Act.

These standards and their requirements create robust frameworks and principles of management, while LCA and LCSA both constitute a powerful tool for the comprehensive assessment of environmental, social and cost impacts. In order to gain from significant synergies, we focused on key clauses to put us in a better position to understand the association between the different standards that might guide us.

Clause 4. Context of the Organization

- Section 4.1. Understanding the organization and its context: Sustainable LCA may allow an organization to identify and assess environmental aspects and impacts of operations, products and services, as well as to find social risks and opportunities. The

consideration of externalities by organizations for the accounting of LCC may also be of relevance for understanding the external context in strategic planning.

- Section 4.2. Understanding stakeholder needs and expectations: LCA brings forth stakeholders concerned with the environmental and social performance and quality objectives and helps an organization meet their expectations by aligning to sustainability objectives assuming both financial and non-financial issues are satisfied.

Clause 5. Leadership

- Section 5.1. Leadership and commitment: QSE and LCA principles are a priority that requires unlimited commitment from the top management down to every single member of the organization. This, therefore, calls for an inclusion of LCA-S findings into QSE policies and objectives.
- Section 5.2. QSE policy: LCA supplies data and information building of this policy with regard to a balance between financial, environmental and social factors.

Clause 6. Planning

- Section 6.1. Actions to be taken in response to risks and opportunities: Use LCA for the identification of environmental, social, and economic risks and opportunities and the planning of all these aspects with sustainability in mind.

Clause 7. Support

- Section 7.1. Resources: Apply sustainability practices, support corporate social responsibility and guarantee financial viability. The harmonization is proof that QSE-relevant resources are committed to the three principles of sustainable development: E, S and E.
- Section 7.2. Competence: Regarding the LCA and QSE system, the responsible personnel shall provide the competence needed when performing traditional LCAs; knowledge about financial aspects connected to the QSE system, such as related economic consequences when decisions are made; and the capability for integrating social elements into the decision-making process.
- Section 7.3. Awareness: Establish and publish LCA results and conclusions on behalf of anybody's interest, decision-makers and the public; transparency is also an essential part of this approach.
- Section 7.4. Communication: Organizations shall have a structured system to address environmental, social and financial communications with the aim of guaranteeing an appropriate and transparent communication of the LCA results to achieve overall sustainability.
- Section 7.5. Documented information: LCA reports and data will provide much-valued documentation in all aspects concerning sustainability and management of the same within the management system.

Clause 8. Operation: LCA information may support the development of processes and procedures to manage and monitor the aspects related to sustainability in operation, as called for by the requirements for effective operational control in ISO 9001, ISO 14001 and ISO 45001.

Clause 9. Performance evaluation: LCA provides the framework to monitor and evaluate environmental, social and financial performance measures linked, respectively, to the environmental, health and safety, and quality management systems.

Clause 10. Improvement

- Section 10.2. Nonconformity and corrective action: LCA finds out the root cause of problems and makes corrective measures to avoid repetition.
- Section 10.3. Continual improvement: QSE, LCA and social responsibility standards all call for continuous improvement. LCA and S-LCA data foster ongoing efforts at

improving environmental impacts and enhancing social performance, in consonance with the commitment of ISO 9001, ISO 14001 and ISO 45001 to continual improvement of the effectiveness of the QSE management system.

3. Survey Analysis Results

The data survey contains several questions related to QSE and LCA management systems, as shown in Table A1. The purpose was to gain insight into how organizations currently manage the LCA framework for sustainability, especially those with a QSE system in place. The survey identified existing practices, challenges and areas for improvement in integrating LCA into QSE management for different company sizes and in various industrial sectors. The survey was completed by Quality, QSE, HSE, R&D and supply chain managers, as they play an important role in implementing the QSE strategy. Their involvement in QSE initiatives and their knowledge of LCA brings an additional layer of expertise on environmental impacts and sustainability, making these organizations highly valuable during the consultation phase. The characteristics of the 127 Moroccan companies that participated in the survey are detailed in Table 4.

Table 4. Characteristics of companies surveyed by number of employees, sectors and participants.

Sectors/Size of Firms	Small	Medium	Large	Total
Number of employees	(1–50)	(50–100)	>100	
Manufacturing and infrastructure industries	4	8	50	62
Consumer Products and Packaging Sector	5	11	18	34
Sevices	9	1	3	13
Transportation and logistics	5		2	7
Design and Engineering	4	2	5	11
Total	27	22	78	127
Respondents' position/Number of employees	(1–50)	(50–100)	>100	
Director	17	1	3	21
Supply chain manager	1	1	1	3
EHS Manager	1	3		4
QSE/QHSE Manager	2	4	40	46
Quality Manager	5	13	26	44
Research and Development Manager	1		8	9

Large firms are present throughout most of the sectors, especially in manufacturing and infrastructure. Managerial positions related to quality, safety, and environmental concerns are more commonly found in larger firms, highlighting their significance within large-scale operations. In contrast, smaller firms tend to rely more on direct leadership from directors, suggesting a more hands-on approach to management within these organizations. This distinction underscores the differences in organizational structure and the allocation of responsibilities between larger and smaller companies. It was important that the respondents have a basic knowledge of the quality and/or safety and/or environmental management techniques incorporated in the ISO 9001, ISO 45001 and ISO 14001 standards and of the tools for assessing environmental impacts at the company level. The diversity of the respondents validates the results obtained, which is in line with the objectives of this study.

3.1. QSE System Adoption

Out of the 402 questionnaires distributed, 127 were returned in good condition. Of these, 104 responses were from companies with an established management system, and 103 activities were certified. The QSE management system framework plays a crucial role in ensuring that organizations not only comply with legal requirements but also meet

customer needs by delivering quality products, maintaining safe working conditions and adopting sustainable practices. This framework supports continuous improvement and fosters a holistic approach to organizational performance. Table 5 provides a clear picture of how organizations are aligning their QSE systems with international standards, with a diverse range of certifications adopted according to the industry's operational and compliance requirements. We introduced a "conformity area" column to enable us to distribute the various standards in terms of quality development, food safety, environmental impact, and occupational health and safety. The results show that there is a deep focus on quality management (56.46%) and environmental sustainability (22.41%) in line with ISO 9001, IATF 16949, EN9100, ISO 22716 and AQAP 2110, ISO 14001, ISO 50001, GLOBAL GAP and SPRING. Health and safety management also receives particular attention, with a rate of 15.10%. This alignment provides a holistic view of how companies are meeting compliance requirements in different areas.

Table 5. Respondents' overview of the industrial certification breakdown according to sector and conformity area.

Standard	Use	Sector	Total Respondents	Conformity Area
BRC [68]	Management of safety and quality food	Food, packaging, retail	1	Food Security and Safety
ISO 22000 [69]		Food industry	6	
KOSHER [70]	Certification of food laws		1	
HALAL [71]			2	
ISO 14001	Environmental MS	Various Environmental sectors	49	Environmental Management
SPRING [72]	Water MS	Water management	1	
ISO 50001 [73]	Energy MS	Various sectors (Energy efficiency)	1	
GLOBAL GAP [74]	Good agricultural practices	Agriculture, farming	1	
GRASP [75]	Social risk assessment for farms		1	Health and Safety Management
SMETA [76]	Ethical audits for supply chains	Various sectors, Supply chains	1	
ISO 45001 [77]	OHSMS/SMS	Various Health and Safety sectors	32	
ATEX [78]	Equipment for explosive atmospheres	Chemicals, Petroleum, Mining	1	
IATF 16949 [79]	QMS	Automotive industry	9	Quality Management
ISO 9001		Various quality sectors	115	
EN 9100 [80]		Aeronautics industry	4	
ISO 22716 [81]	Good Manufacturing Practice (GMP)	Cosmetics industry	2	
AQAP 2110 [82]	NATO quality assurance standards	Defence industry (NATO)	1	

Table 5. *Cont.*

Standard	Use	Sector	Total Respondents	Conformity Area
ISO 27001 [83]	Information Security MS	Data security, Information technology	1	Information security management
PART 21G [84]	Aircraft manufacturing certification	Aircraft manufacturing	1	Aerospace and defense
CAR 573 [85]	Aircraft component maintenance certification	Aircraft maintenance	1	
ISO 17025 [86]	Competence of testing and calibration laboratories	Calibration facilities, Testing laboratories	1	Testing and calibration

3.2. LCA Applications

This section focuses on the survey questions that investigate how companies are involved in life cycle concepts within organizations that already have management systems in place.

- Q.2.3. Are you interested in the Life Cycle concept of your products?
- Q.2.4. If so, in which context?
- Q.3.0. Has your company assessed the life cycle (stages or phases) of its processes, procedures, products and/or services?
- Q.3.1. if so, describe how
- Q.4.1. Do you use software to assess the environmental impact of your products?
- Q.4.2. If yes, please specify?
- Q.4.5. Does your management system include LCA?
- Q.4.7. What are the main barriers to integrating LCA into your QSE management systems?

Statistics will help us determine the level of adoption of life cycle thinking and impact assessment where management systems integration may be necessary. Figure 2 shows that the majority of respondents (59 out of 103, i.e., 57%) showed an interest in the life cycle concept, demonstrating a high level of knowledge and commitment to life cycle thinking (LCT). The largest number of responses, 45%, associated LCT with quality management, followed by 37% of respondents who established life cycle and environmental management. This shows that life cycle considerations are viewed from the perspectives of product quality assurance and environmental management, respectively. Less often, respondents associate it with the concept of the life cycle, which accounts for 18% of health and safety management.

It is essential to determine whether the company has examined the various stages or phases in the life cycle of its processes, procedures, products and/or services. Table 6 shows that the largest number of respondents (35.29%) have assessed the life cycle of their products, followed by 30.15% of companies (22.06%), and only a few organizations (12.50%) have assessed the life cycle of their services.

Table 6. Distribution of LCA across organizational activities.

	Procedure	Products	Service	Processes
Total	30	48	17	41
% Total	22.06%	35.29%	12.50%	30.15%

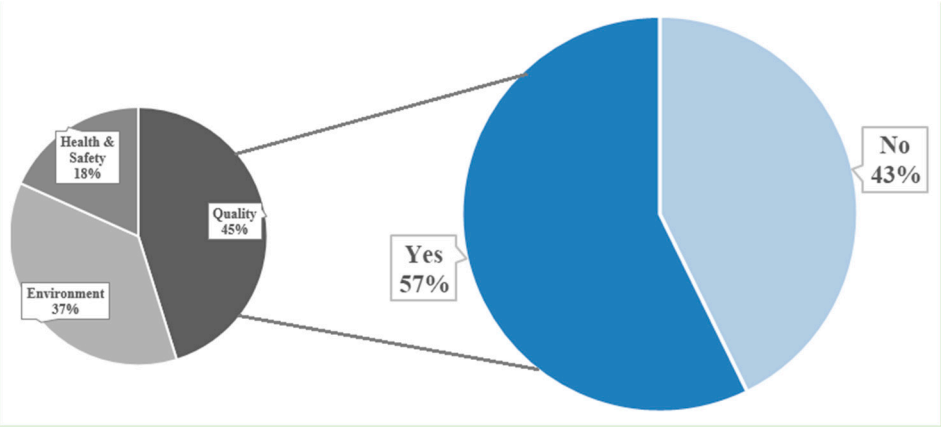


Figure 2. LC thinking in quality, environment, and health and safety.

It is important to know that most companies focus on product LCA, reflecting the importance of quality and sustainability. Many of them also apply LCT to their processes and procedures, with a view to greater efficiency and better cost management, while fewer have assessed services, indicating that the tools or methodological approaches for developing service-related LCA practices are not yet widely applied. We have grouped the answers to question 3.1 into five categories to explain how the organizations' responses align. These include (1) Environmental Compliance and Performance, (2) Value for Money and Waste Management, (3) Energy Efficiency, (4) Product and Process Innovation, and (5) Sustainability Reporting and Communication.

The survey results show that product-focused LCAs dominate in companies, with an emphasis on product quality and sustainability. This is apparent in the category of product and process innovation, where LCA plays an important role in optimizing design processes through CO_2 emission reduction. At the same time, LCA is applied to processes and procedures, showing that many companies want to improve their operational efficiency and are aware of the cost-saving benefits of applying LCT to operational management. Table 7 summarizes the main findings of the survey by category.

In view of previous results on the application of LCA in products, processes, procedures and services, the results show that 40 out of 103 respondents assess the environmental impact of their products and integrate LCA into their MSs with a high level of commitment. Many of these companies integrate LCA into ISO 9001 Quality Management Systems (QMSs) [87] to promote sustainable product development and align it with ISO 14001 Environmental Management Systems (EMSs) to promote continual improvement in environmental performance [26]. Organizations also use LCA-based decision-support systems to match business strategy with regulatory compliance requirements, embrace CE models to encourage waste reduction and resource efficiency [88], and apply eco-design strategies to maximize material selection and minimize the environmental impact [89]. Therefore, even though some organizations (38.83%) are integrating LCA at various stages of their operations, there is still significant scope for progress in terms of adoption. Companies use LCA at various stages of their operations to improve sustainability performance in a variety of industries, including logistics, electronics, automotive and household products. This involves selecting low-impact raw materials [90], cutting production-related energy use and emissions [91], creating environmentally friendly products [92], streamlining logistics to reduce carbon footprints [93], enhancing operational effectiveness during the use phase [1,94] and putting CE recycling end-of-life strategies into practice [95]. Regarding the software tools most commonly used by organizations to assess the environmental impact of their products, the SAP software suite (including SAP 6.0, SAP Business Suite 6.0 [96], and SAP S/4HANA 2019) is the most widely adopted, used by 29.17% of respondents, as shown

in Table 8. Microsoft PLM [97] ranks second at 16.67%. Specialized LCA tools, such as OpenLCA [98] (with free access) 1.10.2 and SimaPro 9.2 [99] and ADEME 3.1.1 [100] (with online access), are used by 12.50% and 8.33% of organizations, respectively. These tools play a key role in supporting environmental impact assessments within the framework of sustainability practices. This diverse range of software proves that companies choose software according to their specific needs, whether it is extensive ERP integration or a more in-depth environmental analysis.

Table 7. Alignement des considérations sur les catégories d'ACV.

Category	In Proportion of	Specifications
Product and process innovation	Quality and Sustainability Product	* Reducing CO_2 emissions * Development of new manufacturing processes * Improving vehicle mass * Engine performance optimization * Evaluation of the industry's environmental sustainability
Energy efficiency	LCT applied to processes and procedures	* Reducing energy consumption (Thermal insulation) * Optimization of resource use * Reducing costs * Control of GHG emissions * Impact minimisation (use of chemicals)
Resource optimization and waste management	Improving operational efficiency and reducing waste	* Waste recycling * Waste elimination (Lean management) * Packaging optimization * Chemicals management
Sustainability reporting and communication	LCA limited to services	* Communication of the industry's environmental footprint * Creation of environmental impact assessment reports * Measuring environmental risks associated with construction projects * Evaluate the environmental impact of food production practices * Promote sustainable practices and development

The diagram in Figure 3 shows the main barriers to LCA integration into QSE management systems. A lack of staff knowledge of LCA methodologies (28.57%) is a major factor blocking integration of the LCA tool and indicates a need for further training and capacity building. Lack of time and difficulties in obtaining reliable and complete data to conduct the LCA are both growing challenges, with a proportion of 23.81% for each. Support from management is essential to foster integration, and its lack can slow down the implementation process and block collaboration between process drivers, while 19.05% of participants cited a lack of support from management. The organizational culture within organizations and attitudes in favor of change are holding back the deployment of LCA, a notable factor for 16.67% of respondents. Limited financial resources represent a moderate concern on the part of respondents, with a rate of 14.29%.

Table 8. Ranking of the software tool of LCA within Moroccan companies.

Software Tool	Total	Total %	Rank
ADEME 3.1.1.	2	8.33%	4
Ecospeed LCA [101]	1	4.17%	5
LCA Calculator [102]	1	4.17%	5
MICROSOFT PLM	4	16.67%	2
OpenLCA 1.10.2	3	12.50%	3
SAP 6.0/SAP Business suite PLM 6.0/ SAP S-4HANA 2019	7	29.17%	1
SimaPro 9.2.	3	12.50%	3
Internal software for the company: BV LCA [103]	1	4.17%	5
Confidential	3	12.50%	3

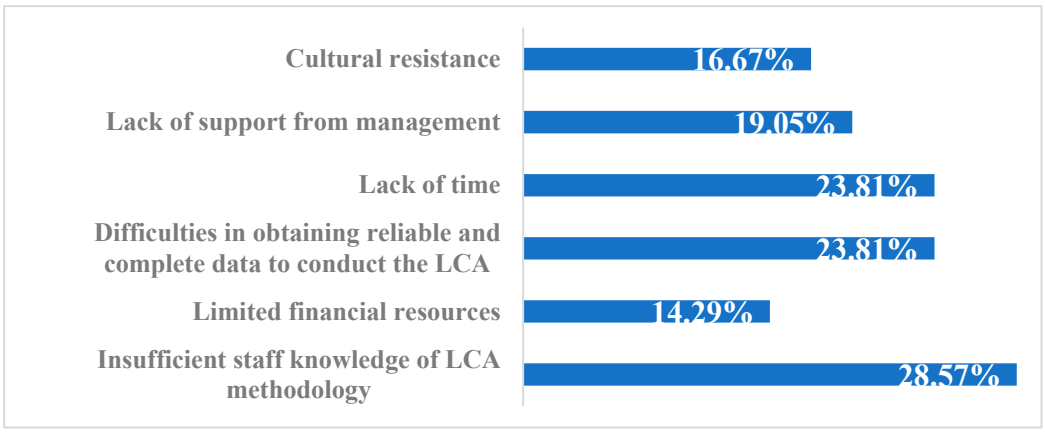


Figure 3. Main challenges in integrating the two LCA-QSE systems.

These challenges depend on the size of the company and its field of activity. According to Table 4, large firms generally have QSE/QHSE managers (40 respondents) and/or R&D managers (8 respondents), which makes it easier to assign LCA resources. Small companies, on the other hand, are more dependent on their directors and have more difficulties in terms of training, specific skills and budget. This distinction highlights the difference in integration capabilities according to the organization's size and sector and underlines the importance of an appropriate support framework.

3.3. Benefits and Recommendations

As shown in Table 9, integration produced positive results for the majority of Moroccan companies. We can conclude that LCA brings many valuable advantages in multiple dimensions. Here are some of the positive points: 14.04% of companies voted for continuous improvement, followed by improving operational safety and innovation for sustainable offerings, with an importance level of 12.28%. Furthermore, 11.11% of companies indicated that the role of LCA in supply chain management is significant, and 10.53% of companies considered commitment to sustainable development to be a key value. Resource optimization, stakeholder engagement, management commitment and long-term strategic decision-making, and the identification and mitigation of environmental risks at a rate of ~6% represent insufficient benefits from LCA. The cost reduction of only 4.09% is not the main benefit of applying LCA, but it is seen as another advantage, particularly in terms

of energy savings and waste reduction. Finally, 3.51% cite both consumer concern for the environment and detailed evaluation.

Table 9. Benefits of integration.

Benefits of Integration	Total	Total %
Management commitment	10	5.85%
Detailed assessment of environmental impacts throughout the product life cycle	6	3.51%
Commitment to sustainability	18	10.53%
Improving operational safety	21	12.28%
Continuous improvement	24	14.04%
Innovation and creation of more sustainable and competitive offers	21	12.28%
Supply chain management (in terms of environmental impact)	19	11.11%
Identification and mitigation of environmental risks at an early stage	9	5.26%
Relevant stakeholder engagement and expectations	10	5.85%
Resource optimisation	10	5.85%
Cost reduction (reducing energy consumption and waste)	7	4.09%
Long-term strategic decision-making	10	5.85%
Environmentally aware consumers and customers are attracted to LCA	6	3.51%

The following questions are designed to help us validate how organizations perceive the long-term evolution of QSE and LCA integration. They will also gather suggestions and improvements to ensure that LCA and QSE frameworks are transparently incorporated into operational practices, fostering seamless integration and enhancing sustainability efforts within organizations.

- Q.5.0. How do you expect the LCA tool to evolve in your QSE systems?
- Q.5.1. What suggestions do you have for better integration of the LCA tool into QSE management systems?
- Q.5.2. What kind of training or development do you suggest for your company to better integrate LCA into QSE systems?

For the recommendation section, and to improve the integration of LCA into QSE management systems, the survey results indicate that the emphasis is on training and collaboration. In other words, key recommendations include empowering those involved with LCA software and encouraging collaboration between LCA experts and managers, while providing practical training through case studies and best practices. There is also growing interest in carrying out simulated audits and providing basic training in LCA principles, underlining the need to build capacity and help organizations achieve easier integration.

The participants highlighted the importance of standardizing LCA procedures, integrating LCA software into QSE systems, and involving stakeholders at all levels, including suppliers and customers. They consider that putting in place LCA experts and providing advanced training to key personnel are essential for long-term success. In the future, respondents expect LCA to become more data-driven, with an emphasis on establishing a robust regulatory framework, integrating LCA into decision-making and promoting the CE as part of wider sustainability efforts.

4. Methodology LCA-QSE Integrating Modeling

4.1. Preliminaries

Several major challenges emerged from both an in-depth literature review and the analysis of the data from this survey. An integrated model of LCSA-QSE was implemented because the problems faced by companies, especially in Morocco, had to be put in touch with their sustainability objectives. First, there was no single framework that unified LCA and QSE systems, which were normally considered on a fragmented basis under ISO 9001, ISO 14001 and ISO 45001 for QSE and ISO 14040/44 for LCA. This fragmentation undermined the effectiveness of linking sustainability performance to operational QSE measures. Additionally, the absence of well-defined procedures for social impact assessment has made it challenging to involve stakeholders and collect comprehensive, reliable data on the environmental, social and economic consequences. Additionally, the repercussion was that fewer employees were trained in LCA techniques, and a shortage of resources further hindered the effective integration of LCA into QSE systems. This lack of training and resources limits the ability of organizations to fully adopt and implement LCA within their operational frameworks. These challenges have underlined the need for a global model integrating LCA and QSE, presenting one general framework encompassing environmental and social dimensions of operational excellence, together with economic ones, and equipping companies with tools necessary for satisfying their legal and sustainability requests.

4.2. Model Description

By using the phases of the QSE management system according to ISO 9001, ISO 14001 and ISO 45001 and the stages of LCSA according to ISO 14040 and ISO 14044, we could build an integration model that connects the QSE and LCA methodologies. The results are shown in Figure 4. This integrating model is based on the QSE policy and the sustainability promises that may orient the operational practices from the perspective of sustainability. PESTEL analysis is also an input for the integration process that links stages of the QSE management system according to ISO 9001, ISO 14001 and ISO 45001 with stages of the LCSA according to ISO 14040 and ISO 14044, whose framework analyzes political, economic, social, technological, environmental and legal factors.

First, PESTEL legal environmental variables offer essential information on the status of the regulatory environment. This helps in keeping the model within the ambit of current legislation and future regulatory changes, such as carbon pricing, solid waste reduction mandates or worker safety regulations. PESTEL identifies risks and opportunities in the external environment that could impact the success of the integration, for example, market demand for green products or the economic cost of implementing new technologies. Other factors that may affect the model's performance in the existing infrastructure are technological changes, such as new LCA software or green manufacturing techniques. Besides these technological, legal, and economic factors, the social dimension is equally crucial to the integration of LCA-QSE. PESTEL mainly takes into account community involvement in sustainable practices, stakeholder expectations, and employee conditions. But it is also important to consider external social considerations, especially for enterprises that operate close to popular geographic areas. Environmental issues, such as noise pollution, odor emissions and deteriorating air quality, may cause opposition to industries like biogas plants or manufacturing facilities. These problems may affect public acceptance, regulatory clearances, and company reputation, which may eventually affect the way LCA-QSE initiatives are implemented. Therefore, regulatory frameworks, environmental risks, and social expectations create high-level strategic alignment between external factors and the operational execution of LCA and QSE systems.

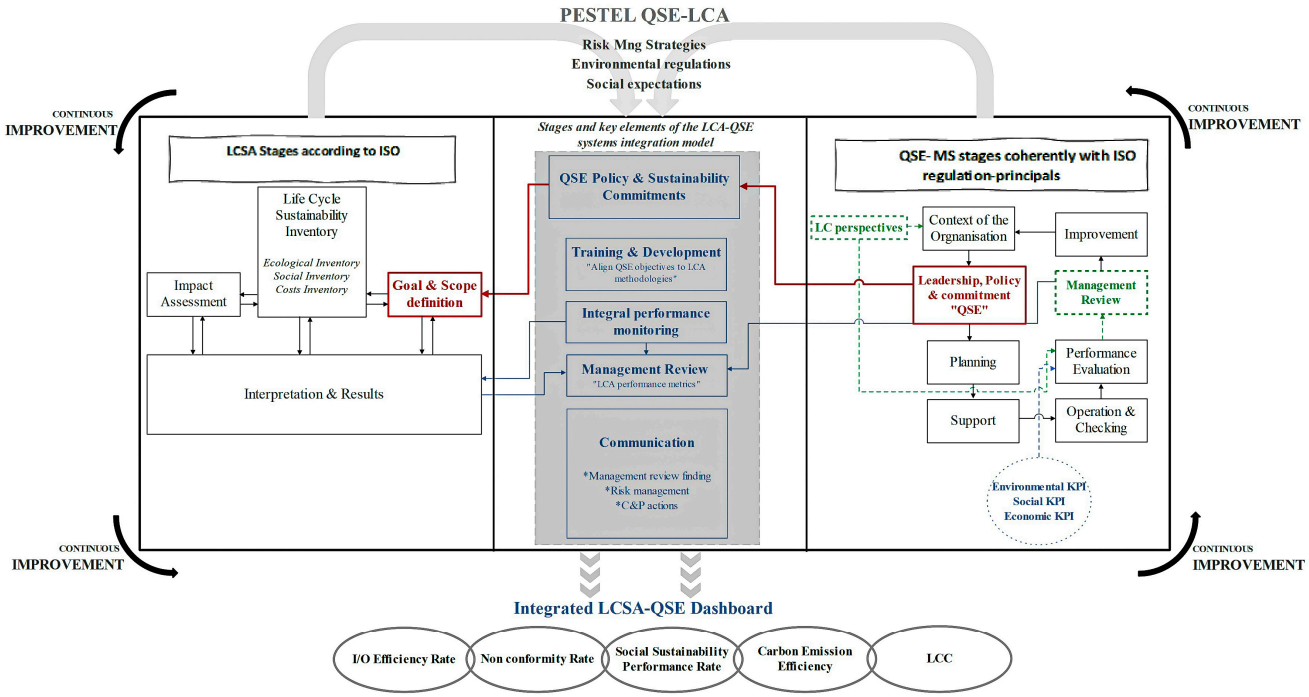


Figure 4. Proposed operational model for integrating LCSA-QSE management systems aligned with the ISO standard.

The left-hand section of the model in Figure 4 represents standard LCA steps, which are ISO 14040/44 in particular, but expands into LCSA, including the three inventories, ecological, social and economic, in the process. The goal and scope of the study set the boundaries [104,105] for the LCSA and define the sustainability goals and identify the functional unit (FU) for assessment [105]. The second order of the life cycle inventory (LCI), engagement with stakeholders, as outlined in ISO 26000, Clause 5.3, is essential during the LCI phase. This is because all key players contributing data to the LCI, such as suppliers providing information on raw material extraction, customers sharing data on product use and regulators offering data on compliance with environmental laws, are crucial to ensuring a comprehensive and accurate inventory. Effective stakeholder engagement ensures that the LCI is well informed and aligned with sustainability and compliance objectives. Then, there is LCA -ISO 15686-5, Clause 4.3, embedding in the environmental consideration the economic consideration at each life cycle stage. The results from inventory are then fed into the LCIA, where sustainability impacts are evaluated and interpreted. The findings provide the basis for continuous improvement in sustainability and operational performance [1]. The right-hand side of the model represents the ISO 9001-, ISO 14001- and ISO 45001-compliant QSE management system stages adapted to take account of the integration of sustainability data from LCA. Lifecycle thinking provides data on environmental, social and economic relationships that are integrated from the outset into the organizational context, then, when key performances derived from the inventory are assessed and reviewed to ensure continuous improvement.

The "Central section", or "Stages and key elements of the LCA-QSE systems integration model", is the middle part, which actually shows the very important point of integration between the two systems. A graphic on this central part shows the representation of LCA results aligned with the QSE approach presented by the organization. QSE Policy and Sustainability Commitments Integration relationships refer to integrating QSE policies and commitments in such a way as to establish the purpose of the LCA. It represents the model's main integration path, which is the essential link between the two clauses: LCA

and QSE-MS. This has provided a very considerable basis for total integration to ensure that sustainable development is integrated into the organization's Q-S and E management right from the beginning. Therefore, instead of having sustainable development as some kind of parallel and independent initiative, it puts the concept right into the core of QSE management by introducing long-term sustainability objectives within the operational and strategic frameworks of the organization. Adding "Training and Development" has been quite important and indispensable since it covers the knowledge gaps of staff, as were identified by the survey. Structured training helps all levels of employees understand the implication of LCA [106] on the three pillars of the management system; this will facilitate the implementation of integrated strategies. Integral performance monitoring means the organization continuously monitors the key sustainability performance indicators (Environmental KPI, Social KPI, and Economic KPI), which are the sustainability impacts measured by the LCA are tracked actively in QSE systems. The "Managements Review" process focuses on "Integral performance monitoring". Management reviews are conducted to assess the integration of LCA into QSE objectives, using cost, environmental and social KPIs as the basis for evaluation. This process ensures that the information is analyzed and reintegrated into the continuous improvement cycle, reinforcing a decision-making process that links LCA results to QSE objectives. The "Communication" section of the model ensures that the results of the management review are communicated, and it explicitly links the conclusions of the management analysis with the results of the risk management and the C&P with the QSE and LCA stages. This is an essential step to make sure that results from life cycle assessment are not only collected but actively communicated and put into practice by the concerned departments themselves. The innovative indicators on the dashboard represent, in fact, the result of integration in three dimensions—environmental, social and economic—two of which are calculated according to the 5M/6M method, corresponding to risk management.

Innovative indicators on the dashboard masked the output of the integration process, considering that it is an integrated result in three dimensions: environmental, social and economic. The calculation is performed according to the 5M/6M method corresponding to material, manpower, environment, methods and measure. All of the model elements described above comply with the PDCA cycle. Such an approach enhances the transparency of a company: it is regulated and follows all the legislation, hence satisfying customers from the sustainability perspective.

4.3. Strategic Decision-Making in the Model

4.3.1. Environmental Dimension in Line with QSE

According to [107,108], four steps are followed to assess the environmental impacts, namely, (1) identifying the inventory components, (2) classifying and characterizing, (3) standardizing, and (4) weighting. The I/O efficiency rate is defined as the monitoring agent for resource efficiency, waste reduction and environmental impact. It is calculated as shown below:

$$\mathrm{IOER} = \frac{\sum \mathrm{Output}}{\sum_{i=1}^{n} \left(R_{method} + R_{machine} + R_{workforce} + R_{measure} + R_{material}\right) * L_i} \quad (1)$$

where:

- Output: Total amount produced and/or value-added per department;
- Rmethod: Input resource related to method efficiencies;
- Rmachine: Input of resources referring to energy and maintenance consumption;
- Rworkforce: Workforce-related resources such as working hours;

- Rmeasure: Resources associated with measures (quality control, calibration, testing, etc.);
- Rmaterial: Resource materials used in the production system;
- Li: Weighting factor for each type of resource;
- n: Overall quantity of resources.

And the sustainability indicator Carbon Emission Efficiency CEE is

$$\mathrm{CEE} = \mathrm{CEE}_1 + \mathrm{CEE}_2 = \frac{\sum \mathrm{Outputs}}{\sum \mathrm{CO_2Emissions}} \quad (2)$$

where

$$\mathrm{CEE}_1 = \frac{\sum(\mathrm{Units} + \mathrm{Value} + \mathrm{Energy} + \mathrm{Service})}{\sum(\mathrm{M_{iGAZ}} * \mathrm{GWP_i}) + \sum(\mathrm{QtyofMat_i} + \mathrm{EgyConsumed_i} + \mathrm{Dist_i} + \mathrm{LTEgy_i}) * \mathrm{EmisFtr_i} * \mathrm{L_i})} + \frac{\sum(\mathrm{Units} + \mathrm{Value} + \mathrm{Energy} + \mathrm{Service})}{\sum \mathrm{Amnt\ of\ Wste_i} * \mathrm{EmisFtr_i}/\mathrm{Recycl_i} * \mathrm{L_i}} \quad (3)$$

where

- MiGAZ: Mass of i-GHG emitted;
- GWPi: Global Warming Potential of i-GHG emitted;

$$\mathrm{M_{iGAZ}} = \mathrm{n} * \mathrm{M} \quad (4)$$

- $\sum \mathrm{Qty\ of\ Mat_i} = \mathrm{Qty\ of\ materials\ used_i}$;
- EmisFtri: Material emissions factor in 'kg CO_2/kg material';
- Li: Weightning factor for each type of resource;
- Disti: Distribution and transport;
- LTEgyi: Energy consumed over consumption lifetime;
- Amnt of Wstei: Estimated quantity of waste or scrap;
- Recycli: Emission factor for recycling;

and

$$\mathrm{CEE}_2 = \frac{\sum(\mathrm{Units} + \mathrm{Value} + \mathrm{Energy} + \mathrm{Service})}{\sum \mathrm{EmisFct_i}(\mathrm{Workforce} + \mathrm{Machine} + \mathrm{Method} + \mathrm{Measure})} \quad (5)$$

where

- $\sum \mathrm{Workforce_i} = \mathrm{Travelled\ Distance_i}$;
- $\sum \mathrm{Machine_i} = \mathrm{Mce\ related\ Emis_i}$;
- $\sum \mathrm{Method_i} = \mathrm{Extra\ Resources\ Used_i}$;
- $\sum \mathrm{Measure_i} = \mathrm{Egy\ Consumed\ by\ measure\ tools}$;

The GWP values for the various GHGs are based on research and scientific modeling and therefore are usually found within scientific literature on climate, for instance, from reports from the Intergovernmental Panel on Climate Change (IPCC) [109]. There is a 100-year time frame for GWP (see Table 10 for GWP values of some GHGs [110]).

Table 10. GWP value of some GHGs on a time horizon of 100 years (elaborated by [110]).

GHGs	Time Horizon of 100 Years
Dioxide carbon (CO_2)	1
Methane (CH_4)	25
Nitrous oxide (N_2O)	298
Hydrofluorocarbon (HFCs)	124–14,800
Perfluorocarbon (PFCs)	7390–12,200
Chlorofluocarbon (CFCs)	4750–14,400

4.3.2. Social Dimension in Line with QSE

This dimension is proposed to analyze social indicators linked to sustainability. These include the Social Sustainability Performance Rate. The identification of stakeholders is mandatory as part of the social analysis integrated into the MS-QSE. The Social Sustainability Performance Rate or S-SPR monitors the company's performance in terms of its contribution to social well-being. This indicator involves working conditions, health and safety in accordance with ISO 45001, gender equality, impact on society, employee satisfaction (internal human resources providers to be measured in accordance with ISO 9001, "Internal customer satisfaction") and human rights (ISO 26000). Environmental justice, which makes sure that disadvantaged communities, especially lower-income populations who live close to industrial sites, are not significantly impacted by industrial activity. Facilities like waste treatment facilities, chemical processing facilities, and biogas plants can cause environmental problems, including,

- Odor nuisances and air pollution;
- Risks of water contamination;
- Traffic delays and noise pollution.

These categories rely on qualitative and quantitative data (audits, analysis of staff appraisals...), and for each impact category, it is assigned a weighting factor according to the importance of each category for the organization and/or its stakeholders. Therefore,

$$S - SPR = \sum (P_i * L_i) + (Pej * Lej) = (P_{Wk} * L_{Wk}) + (P_H * L_H) + (P_S * L_S) + (P_{ES} * L_{ES}) + \ldots + (P_n * L_n) + (Pej * Lej) \quad (6)$$

where

- Pi: Performance score for each social i-category (working conditions, health and safety, gender equality, impact on society, employee satisfaction and human rights;
- Li: Weighting factor for each social i-category;
- P_{WK}: Performance score for working conditions;
- P_H: Performance score for health;
- P_S: Performance score for safety;
- P_{ES}: Performance score for employee satisfaction;
- L_{WK}: Weighting factor for working conditions;
- L_H: Weighting factor for health;
- L_S: Weighting factor for safety;
- L_{ES}: Weighting factor for employee satisfaction;
- P_{EJ}: Performance score for environmental justice, based on environmental impact mitigation strategies and nearby affected communities;
- L_{EJ}: Weighting factor for environmental justice impact (stakeholders' perception);

Table 11 shows the ranked results for the social dimension of LCA-QSE integration, and provides a calculation framework for the S-SPR indicator where five stakeholders and eight groups are identified.

Table 11. Framework envisaged for the S-LCA dimension of the LCA-QSE model.

Stakeholders	Class	Social Impact KPI	Stages			
			Production	Use	Distribution	End of Life & Recycl
Workers	Work hours	working hours rates	x	x	x	-
	Health and Safety	Safety in the workplace, incidents related to health at work	x	x	-	x

Table 11. *Cont.*

Stakeholders	Class	Social Impact KPI	Stages			
			Production	Use	Distribution	End of Life & Recycl
Community	Local community	% of local employees engaged	x	-	-	-
	Health effect	Noise and Air impact	x	-	-	x
	Environmental justice	Communities near industrial impact zones at risk	x	x	-	x
Supplier	Local sourcing	Supply chain sustainability	x	-	-	-
Society	Technology development	% Use of new technologies	x	x	-	x
Consumer	Responsibility for the product	Health and safety of consumers	-	x	-	x

4.3.3. Economic Dimension in Line with QSE

LCC can provide an overview of the financial consequences of decisions [20,111]. When it comes to assessing projects that deal with sustainable development, it is very advantageous, as with its application, it is possible for the decision-maker to evaluate different available alternatives in relation to both short- and long-run cost implications by considering the life cycle perspective [112]. In the model for total cost of sustainability, the diagram will follow the 6M of the Ishikawa method and will comprise

$$LCC = C_{material} + C_{medium} \sum_{t=1}^{n} \left(\frac{C_{method} + C_{machine} + C_{workforce} + C_{measure} + C_{oth}}{(1+r)^{t}} \right) + \frac{C_{edl}}{(1+r)^{n}} \quad (7)$$

where

- Cmaterial: Sum of all costs of different raw materials for each service provider;
- Cmedium: Cost linked to the work environment that could influence the product or service including safety, health measures and compliant work environment;
- Cmethod: Costs of procedures, information flows, R&D and instructions used;
- Cmachine: Cost of machines needed to produce the product or perform the service;
- Cworkforce: Cost of human resources involved;
- Cmeasure: Cost of checking errors in measurements that could be the cause of the problem;
- Coth: Other costs that could be associated with delays [113], transport [107] or replacements;
- Cedl: Deadline costs or end-of-life costs of scrap and/or recycling;
- t: Time or period;
- r: Rate of reduction/discount;
- n: Total utilization and operating time.

Non-conformities directly affect the cost, profitability and operational efficiency. Some non-conformities may increase costs due to reprocessing, scraps, or recalls. They may further lead to lost sales, certification in the case of major issues and damage to brand reputation. Non-conforming products can make the supply chain less efficient, with further economic implications.

$$NCR = NCR_{Services} + NCR_{products} \quad (8)$$

Normally, the two broad divisions of NCR include product non-conformity and service non-conformity. The service non-conformities are calculated based on an internal audit carried out. The NCR is estimated as follows. The cause-to-effect methodology involves

the analysis of the non-conformities, as much as the human factor or manpower/staff, understood as human errors, mistakes and training delivered poorly or ineffectively, while affecting the quality of the product and service. The same occurs with equipment failures or adjustment defects, which cause production flaws and the interruption of services in productive environments.

Material cause: The material cause focuses on how defective or inconsistent raw materials contribute to the non-conformity of products and how poor-quality resources contribute to service efficiency. Processes, procedures and work instructions are a normal cause of non-conformity. The defective products lead to production, and in service, it leads to the failure of the delivery service.

This LCA-QSE integration framework has been designed to meet the practical challenges faced by companies in adopting LCA. By aligning the stages of LCA standards (ISO 14040/44) with the requirements of QSE management systems (ISO 9001, ISO 14001 and ISO 45001), it provides a consistent and progressive framework for integration, based on an existing organizational structure. This helps companies to overcome standard challenges such as methodological complexity, lack of training or limited data availability by introducing sustainability KPIs that provide drivers for continuous improvement. In addition, the PESTEL analysis included in the framework enables companies to anticipate external regulatory and social pressures.

By adopting this model, companies can create a clear roadmap for integrating sustainability into all levels of management.

5. Discussion

The literature review conducted for this study identified the deficiencies in the current frameworks that integrate LCA into QSE management systems. Fundamental works begun by Kloepffer 2008 [20] and Zamagni et al. 2012 [11] introduce the inclusion of the LCC and S-LCA alongside the traditional environmental LCA, the E-LCA. However, significant challenges persist concerning data collection and the non-availability of standardized approaches to integrate economic and social matters within the LCA. It should be noted that these issues are not distinctive of the present study and are commonly acknowledged from the literature; let us just mention, for example, scholars such as Guinee 2016, Alejandrino 2021 [114,115], and several other researchers underlining the balance of these dimensions in practical applications. The survey results from Moroccan industries indicate that the integration of LCA into QSE management systems varies across sectors, depending on the industry in which they operate. Firms operating in manufacturing and infrastructure are actually advanced, while small companies face huge barriers due to financial constraints and lack of training. This finding aligns with the studies in [116], which observed that SMEs face resource-intensive challenges when conducting comprehensive life cycle analyses. This comparison underlines the fact that even though larger organizations are in a better position to implement LCA within the QSE system, gaps in knowledge, resources, and standardization are still relevant. Similarly, Sala et al. (2020) [58] highlighted that the complexity of LCA methodologies often discourages smaller organizations from fully adopting sustainability assessment tools. This comparison underlines the fact that even though larger organizations are in a better position to implement LCA within the QSE system, gaps in knowledge, resources and standardization are still relevant.

The findings of this study confirm that integrating LCA into QSE management systems is a strategic tool for improving sustainable performance. Among the 103 companies surveyed, 40 are already assessing the environmental impact of their products and are integrating LCA into their management systems to a high degree of commitment. Some

38.83% of respondents are applying LCA at various stages of their operations (products, processes and services), reflecting a progressively but still incomplete adoption.

The KPIs in the LCA-QSE model developed in this study include metrics such as "Carbon Emission Intensity," "Resource Efficiency," and the "Social Performance Index." These indicators offer a more comprehensive framework for evaluation, surpassing the conventional environment-centric focus typically associated with LCA. In contrast to models like that of Mazzi et al. (2017) [33], where environmental KPIs are emphasized, the integrated model developed here integrates social and economic dimensions, offering a more holistic view of sustainability performance. This broader approach ensures a balanced assessment across all pillars of sustainability. This falls in line with the recent trend in Life Cycle Sustainability Assessment, or LCSA, which intends to map all areas of sustainability impacts. The emphasis hereby is mainly on social indicators in line with ISO 26000, which puts a special focus on social responsibility. This model introduces an innovative approach compared to earlier frameworks, which similarly underrepresent the inclusion of social aspects. The contribution of this study lies in integrating ISO standards, such as ISO 9001, ISO 14001 and ISO 45001, with the LCA stages outlined in ISO 14040/44. This integration provides a highly practical framework for organizations seeking to incorporate sustainability into their operational processes. In fact, QSE policies aligned with the LCA stages will ensure that the aspect of sustainability is rooted not only on the strategic level of planning but also in day-to-day operations when brought into practice, as discerned by Hauschild et al. (2018) [32]. The use of PESTEL analysis in addressing the external political, economic, social, technological, environmental and legal factors provides an added strategic advantage to organizations in being prepared for regulatory challenges by continuously updating of processes for the required adjustments. All of these are set within the wider framework that overcomes many of the limitations evident in earlier studies, such as Beier et al., 2022 [43], where digital tools for monitoring the environment were reviewed with the limited incorporation of the social and economic dimensions of sustainability.

This study provides a more comprehensive framework by integrating PESTEL, which enables companies to adapt their sustainability plans to market and regulatory developments. In addition, Zamagni et al. [11] have illustrated how LCA can promote regulatory compliance and improve market positioning. They provided detailed data on environmental performance. Wender et al. [117] have also explored the role of LCA in regulatory decision-making, proposing a case study analysis of how LCA supports compliance. This is consistent with our research, which indicates that companies that include LCA in QSE systems are better equipped to meet future sustainability standards and gain the benefits of improved environmental and social governance (ESG) performance. Curran [118] highlighted the role of LCA and defined the objectives and scope of sustainable product design, ensuring that environmental considerations are integrated into the product development process. Andrews et al. [119] explained how companies have used LCA to make informed decisions to reduce their environmental footprint.

Results from the survey also underlined that large companies adopt LCA in their QSE strategies more easily, as opposed to SMEs, which express a need for specific support to overcome some of the barriers to the LCA-QSE integration: knowledge about LCA methodologies by the staff, lack of time and resource constraints. These findings are in line with the literature on LCA adoption, as already pointed out by Wangel et al. (2013) [120], who identified comprehensive training and capacity building as decisive for the successful introduction of LCA in decision-making. Similarly, Kamble et al. (2022) [121] and El Haouat et al. (2024) [94] highlighted the necessity of digital technologies to enhance data accessibility and accelerate LCA implementation.

This study suggests standardizing processes for incorporating LCA into QSE systems, working with LCA specialists and providing hands-on training. This aligns with suggestions from Hellweg and Milà Canals (2014) [122] and Sonnemann and Vigon (2020) [45] who have examined the LCA assessment indicators that are essential for continuous improvement, structured implementation strategies and continuous employee training. Moreover, current research underlines how digital technologies are becoming progressively more important in LCA-based evaluations. Kamble et al. [121] underlined the significance of digital twins and their association with Internet of Things (IoT) data for real-time LCA integration, allowing the environmental footprints to be monitored and optimized throughout the life of the system. From a different perspective, Beier et al. [43] have analyzed the impact of digitalization on QSE frameworks, emphasizing the reduced effort required during LCA due to the benefits of process integration offered by this technology. In this regard, the study develops an integrated model of LCA and QSE management systems and therefore acts as a milestone in embedding sustainability within industrial operations. Based on the findings of the survey and the previous guidelines, this study proposes a more solid and practical approach to the integration of LCA-QSE, which can be applied to a diverse industrial sector to promote sustainable performance at different levels of organizational maturity.

6. Conclusions

This research develops both theoretical and practical advancements through a combined effort of a literature review, empirical questionnaire survey and developing the LCA-QSE model. The results show how fragmented current LCA and QSE management system approaches are, with operational excellence and sustainability goals frequently implemented differently under different requirements. The absence of focus on social aspects in these frameworks is an important issue that this study resolves by taking a more comprehensive approach. This study provides a holistic approach by combining economic and social elements, which makes sustainability evaluation closer in line with international regulatory and industrial objectives than previous approaches that primarily focused on environmental impact assessment.

According to survey results, efficient data management, leadership commitment and training for employees are essential for successful LCA-QSE integration, though adoption is limited by issues including a lack of understanding, data limited availability and a lack of resources. The suggested model provides a systematic framework that incorporates environmental, social and economic aspects in order to close these gaps and provide an appropriate and holistic approach to assessing sustainability.

This study provides an efficient framework to promote LCA-QSE integration, ensuring compliance with sustainable goals while supporting efficient operations and continual improvement. Future studies ought to include sustainability performance indicators, especially those that address economic implications, and investigate how digital technologies might optimize real-time LCA data collecting. Improving and evolving LCA-QSE integration for broad adoption will require increased cooperation between industry, lawmakers and technology developers.

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Appendix A

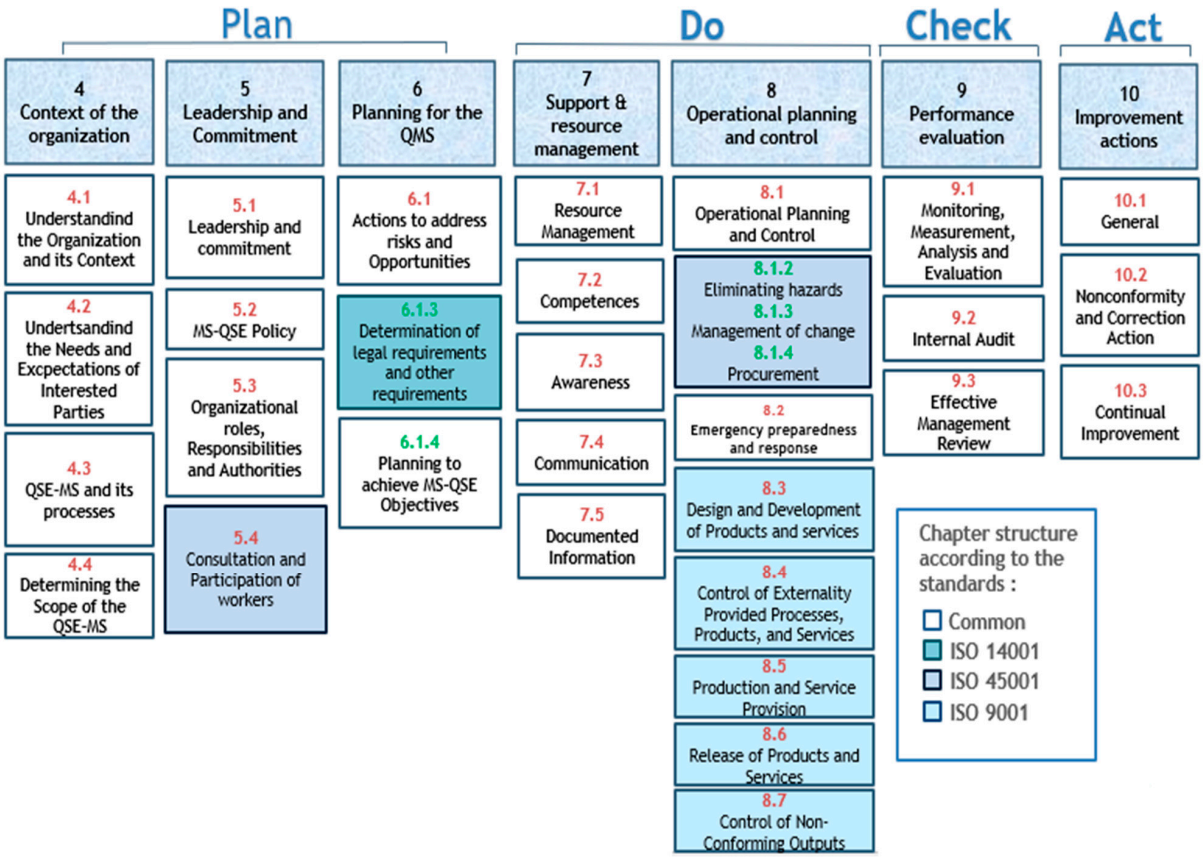


Figure A1. Chapter structure of ISO 9001 V2015, ISO 14001 V2015 and ISO 45001 V2018 standards.

Table A1. Survey on life cycle assessment and QSE management systems (part of integrating the two systems).

Section 1: Company profile	
1.0 Company name: (optional)	
1.1. Your company is (Legal_form)	SARL SA SNC
1.2 Your company is in the sector	Private Public
1.3 Sector of activity	*Construction *Health and hygiene * Food Industry *Clothing and Textiles *Distribution and Logistics *Packaging *Automotive *Other: .....

Table A1. *Cont.*

1.4. Role of the respondent in the company?	*Director *Quality Manager *Research and Development Manager *EHS Manager *QSE/QHSE Manager *Supply Chain Manager
1.5 Size of company: (number of employees)	*Small: Less than 50 people *Medium: Between 50 and 100 people *Large: more than 100 people
Section 2: QSE Management systems	
2.0 Does your organization have a Management System?	Yes No
2.1 Does your organization have ISO certification?	Yes No
2.2 If yes, which standard?	*ISO 9001 *ISO 14001 *ISO 45001 *Other: . . ....
Q.2.3. Are you interested in the Life Cycle concept of your products?	Yes No
Q.2.4. If so, in which context?	*Quality *Environment *Health and Safety
2.5 How management systems make your work easier (Benefits)	*Performance assessment *Risk management *Decision-making *Work resource optimization *Quality control and assurance *Inter-departmental coordination *Information feedback
2.6 How do you evaluate the efficiency of your management system?	*Low *Medium *High *Very High
2.7 How do you identify opportunities for improvement within your QSE management system?	*Customer complaints *Employee suggestions *Data quality improvement *Internal Audits *Consideration of resource efficiency *Depth risk analysis
2.8 How do you monitor and measure the efficiency of your system's improvement actions?	*Data analysis *Key Performance Indicators (KPIs) *Lifecycle analysis *Trend analysis *Other: .....
Section 3: LCA Practices	
Q.3.0. Has your company assessed the life cycle (stages or phases) of its processes, procedures, products and/or services?	*Products *Processes *Procedure *Service
Q.3.1. if so, describe how	
3.2. In which extent are environmental indicators linked to LCA included in your MS?	*Fully integrated *Largely integrated *Partially integrated *Not integrated
3.3. What is your perception of the relevance of LCA for QSE management systems?	*Very relevant *Relatively relevant *Mildly relevant *Not relevant
3.4. Do you work with suppliers, customers or other stakeholders to assess the environmental risks of your products/services?	Yes No

Table A1. *Cont.*

3.5 How do you measure environmental aspects and impacts within your company?	*Measures to prevent pollution *Environmental impact assessments *Regular environmental audits
3.6 Do you have indicators to measure, monitor and analyse the life cycle of your products/services?	Yes No
3.7 If yes, please specify	
3.8 How do you study the life cycle of your products/services?	*From cradle to use *From cradle to expiry *From cradle to recycling
Section 4: Integration of LCA and QSE	
4.0 Do you assess the impact of your products on the environment?	Yes No
Q.4.1. Do you use software to assess the environmental impact of your products?	Yes No
Q.4.2. If yes, please specify?	
4.3 Do you have a procedure for conducting a life cycle assessment?	Yes No
4.4 Does your quality management system (QMS) or environmental management system (EMS) or your management system in general encourage the carrying out of a life cycle analysis or feedback on this analysis?	Yes No
Q.4.5. Does your management system include LCA?	Yes No
4.6 What benefits has your company gained from integrating LCA into its QSE systems?	*Management commitment *Detailed assessment of environmental impacts throughout the product life cycle *Commitment to sustainability *Improving operational safety *Continuous improvement *Innovation and creation of more sustainable and competitive offers *Supply chain management (in terms of environmental impact) *Identification and mitigation of environmental risks at an early stage *Relevant stakeholder engagement and expectations *Resource optimization *Cost reduction (reducing energy consumption and waste) *Long-term strategic decision-making *Environmentally aware consumers and customers are attracted to LCA
Q.4.7. What are the main barriers to integrating LCA into your QSE management systems?	*Insufficient staff knowledge of LCA methodology *Limited financial resources *Difficulties in obtaining reliable and complete data to conduct the LCA *Lack of time *Lack of support from management *Cultural resistance
Section 5: Recommendations	
Q.5.0. How do you expect the LCA tool to evolve in your QSE systems?	
Q.5.1. What suggestions do you have for better integration of the LCA tool into QSE management systems?	
Q.5.2. What kind of training or development do you suggest for your company to better integrate LCA into QSE systems?	

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