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A human-centric analysis of life cycle assessments: development and validation of a subject-oriented model

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ABSTRACT

The European Union aims to reach net-zero greenhouse gas emissions by 2050, with a target of at least a 55% reduction by 2030 compared to 1990, to mitigate climate change. This requires various institutions to perform life cycle assessments (LCAs) to assess their environmental impacts. LCA endeavours are non-trivial, and understanding or at least accepting the according processes or better incorporating them in an organisation's operations is paramount. This paper presents a subject-oriented reference model for LCAs. The model was developed by integrating findings from a deductive analysis and improved iteratively through expert feedback. The model clarifies individual roles within the LCA process and is visualised through diagrams that improve understanding for both experts and novices. The evaluation survey affirmed that the model is in line with established norms and can serve as an educational tool for newcomers to the field. The model not only serves current educational and practical needs, but also sets the foundations for a human-centric approach to LCA that can be implemented in the future.

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Life cycle assessment; LCA guide; referential process model; subject orientation; PASS; education

1. Introduction

In the year 2021, the European Commission launched the concept of Industry 5.0 with the objective of promoting an industrial landscape in Europe characterised by sustainability, a focus on human well-being, and robustness (Cotta et al. 2021b). The drive towards a sustainable industry was previously emphasised through initiatives such as the European Union's Green Deal, which outlined bold objectives aiming to significantly cut greenhouse gas emissions by the year 2050 (European Commission 2019). Meeting these ambitious targets involves wide-ranging transformative shifts across numerous sectors, particularly in production methodologies, necessitating the development and integration of innovative solutions into current industrial frameworks. To fully grasp the environmental repercussions of the suggested modifications and to reach the ambitious goals set forth for *sustainable manufacturing*, it is imperative to conduct thorough environmental evaluations as a foundational step. LCA, a method to assess the environmental impacts of products and services throughout their life cycle (Rebitzer et al. 2004), is central because it allows policymakers, businesses, and other stakeholders to identify the stages in the life cycle of products and services where the most significant environmental impacts occur. By understanding these impacts, they can make informed decisions on where to focus efforts to reduce greenhouse gas emissions effectively. For example, LCA can reveal whether it is more beneficial to reduce emissions during the production phase, improve the efficiency of the use phase, or enhance end-of-life recycling processes. Although LCAs are well established in research (Jacquemin, Pontalier, and Sablayrolles 2012), there are complexities, such as defining optimal system boundaries for companies (Heidrich and Tiwary 2013). In practice, determining these boundaries is not straightforward, as it requires careful consideration of various factors such as the scope of the environmental impacts being assessed, the specific goals of the company, and the industry standards that may differ across sectors. For example, a company might struggle to decide whether to include only direct emissions from their production processes or to also account for indirect emissions from upstream suppliers and downstream users. This decision can lead to variations in LCA results, making it difficult to compare results between different studies or generalise findings.

There is a potential to improve existing LCA documentation to make it more user-friendly and supportive for practitioners (Hetherington et al. 2014). Currently,

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many of the available materials do not engage effectively with the practitioners responsible for the implementation of these complex methodologies. One of the main issues is that the documentation often fails to bridge the gap between theoretical concepts and practical application. Practitioners, particularly those who may not have a deep background in environmental science or LCA-specific knowledge, often find themselves overwhelmed by the technical jargon, complex models, and extensive datasets that LCA documentation typically includes. This disconnect can hinder the successful adoption of LCA in business and industry settings, where time constraints and the need for actionable insights are critical. Furthermore, the lack of clear, concise and easily navigable documentation can lead to inconsistent application of LCA methodologies, resulting in varying levels of accuracy and reliability in the outcomes. Furthermore, current materials often do not connect with their intended users, who are tasked with implementing these methodologies (Gutowski 2018). Documentation often does not adequately address the real-world challenges faced by practitioners, such as integrating LCA into existing business processes, managing data gaps, or dealing with variability in supply chain information. This can make it difficult for practitioners to see the relevance of LCA results to their specific context, leading to under-use or misinterpretation of the findings.

To address these challenges, our study used the subject orientation (SO) paradigm, a *human-centred methodology* for process modelling. By focussing on the roles and perspectives of various human actors involved in the LCA process, we conducted a detailed analysis that revealed the underlying complexities and challenges. The result is a subject-oriented reference model that improves understanding of the roles of various stakeholders within the LCA framework.

The developed model serves not only as a practical guide, but also as an educational tool, designed to facilitate the learning and application of LCAs.

The structure of this work will first guide the reader through the theoretical foundations of the topics of LCA and SO (Section 2), then through the related works (Section 3), followed by a description of the research methodology and approach (Section 4) used to design the actual subject-oriented reference model for LCAs that we present in Section 5. This will be followed by the validation of the model (Section 6) and a discussion (Section 7). The study will be finalised by a summary and outlook (Section 8)

2. Theoretical foundation

In the following section, the theoretical foundations of the relevant literature are presented. First, different LCA methodologies are highlighted, followed by an overview of the four phases involved in an LCA study and the corresponding ISO standards that regulate them. The importance of organised and human-focussed methods is highlighted in a separate subsection. This is followed by an introduction to subject-oriented process modelling using Parallel Activity Specification Schema (PASS).

2.1. Life cycle assessment

2.1.1. Types of LCA

LCAs are crucial tools for quantifying the potential environmental impacts of products, services, or entire companies (Vilches, Garcia-Martinez, and Sanchez-Montanes 2017). LCAs can be categorised on the basis of their focus and scope into several types.

Two primary approaches are recognised in the literature and practice: Attributional LCAs (ALCAs) and Consequential LCAs (CLCAs). ALCAs distribute environmental impacts throughout the life cycle of a product, ensuring the inclusion of processes interconnected by energy or material flows, operating under a static technosphere (Curran, Mann, and Norris 2005; Finnveden et al. 2009; Soimakallio et al. 2015).

In contrast, CLCAs examine the environmental impacts that arise from specific decisions, such as changes in product demand, using a more dynamic technosphere (Yang 2016). This approach allows flexible modelling to evaluate coproducts, employing strategies such as substitution or accounting for additional consumption (Schaubroeck et al. 2020; Weidema et al. 2018).

Beyond these, simplified LCAs provide a less resource intensive alternative, requiring fewer resources, time, and effort, while yielding results comparable to full LCAs (Hur et al. 2005).

In addition, Life Cycle Sustainability Assessments integrate environmental, social, and economic indicators, providing a comprehensive view of sustainability.

Additional specialised methodologies include Life Cycle Costing (LCC), which focuses on the economic aspects throughout the life cycle of a product (Hunkeler, Lichtenvort, and Rebitzer 2008), and Social LCAs (S-LCAs), which evaluate potential social impacts related to products or services (Jørgensen et al. 2008).

LCC aims to capture the cumulative costs associated with a product or system throughout its life cycle, considering aspects from production to disposal (Hunkeler, Lichtenvort, and Rebitzer 2008). By evaluating parameters such as labour rights, community involvement, and health implications, S-LCA offers a holistic view of the societal consequences tied to products or services.

Table 1. Overview of different LCA types.

LCA Type	Focus / Scope	Key Characteristics
ALCA	Distributes environmental impacts across all processes in a product's life cycle.	Operates under a static technosphere; connects processes via energy and material flows.
CLCA	Evaluates changes in environmental impacts stemming from specific decisions (e.g. shifts in product demand).	Employs a dynamic technosphere; allows flexible modelling of coproducts (e.g. via substitution or additional consumption).
Simplified LCAs	Provides a streamlined assessment requiring fewer data and less effort.	Generates results broadly comparable to full LCAs, yet demands fewer resources (time, finances, personnel).
LCSAs	Integrates environmental, social, and economic indicators for a holistic view of sustainability.	Goes beyond traditional LCAs by encompassing multiple pillars of sustainability in one framework.
LCC	Focuses on economic aspects throughout the product life cycle.	Captures costs across production, operation, end-of-life, and disposal stages.
S-LCAs	Assesses social impacts tied to products or services.	Evaluates labour rights, community involvement, health implications, and other social factors.

An overview of the various types of LCA is presented in Table 1.

The forthcoming research will focus on an ALCA approach due to its comprehensive capability to assess environmental impacts, adherence to regulatory standards, and practicality in improving environmental sustainability.

2.1.2. The LCA process and relevant ISO norms

The process of conducting an LCA is guided by the ISO 14040:2006 and ISO 14044:2006 standards, which involve four primary phases: Goal and Scope Definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation, as illustrated in Figure 1 (International Standard ISO 14040:2006 2006; International Standard ISO 14044:2006 2006).

The initial phase, Goal and Scope Definition, establishes the study's framework and objectives, ensuring alignment with its intended purpose (Curran 2017). This phase sets the foundation for the methods and boundaries used throughout the LCA.

The LCI phase follows, compiling an exhaustive inventory of inputs and outputs for the product or process throughout its life cycle, including the raw materials, manufacturing, use, and disposal phases (Suh and Huppes 2005). This inventory must adhere to the established goal and scope to ensure consistency and transparency.

In the LCIA phase, the potential environmental impacts of the inventory's inputs and outputs are characterised and evaluated. This is achieved using various standardised impact categories and indicators. For example, the Global Warming Potential (GWP) is a commonly used impact category that measures the potential contribution of a given amount of greenhouse gases to global warming over a specific time period, typically 100 years. The impact indicator of GWP is expressed in terms of carbon dioxide equivalent (CO2e), which converts the impact of all greenhouse gases into the equivalent amount of CO2 that would have the same global warming potential. This standardised approach helps quantify and compare the impacts of climate change of different products or processes in a clear and uniform manner. Examples of different LCIA methods are ReCiPe, Eco-indicator 99, CML2001, or Environmental Priority Strategy (da Silva, Barbosa-Povoa, and Carvalho 2020; Goedkoop et al. 2009; Guinee 2002; Hemdi, Saman, and Sharif 2013). Each method provides different perspectives on sustainability, from holistic views to damage-oriented assessments.

The final phase, Interpretation, involves analysing the LCI and LCIA results to draw conclusions, make recommendations, and communicate findings to stakeholders.

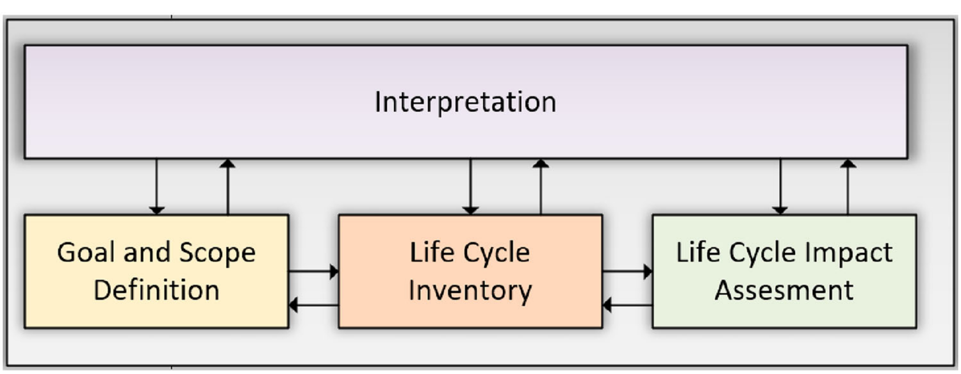

Figure 1. The four *'Phases'* of an LCA (International Standard ISO 14040:2006 2006).

This phase is crucial to support informed decision making and identify opportunities to improve environmental performance and future research (Hauschild, Bonou, and Olsen 2018).

The LCA process is inherently iterative, with insights from later phases potentially influencing earlier ones. Interpretation occurs simultaneously with all phases to ensure continuous alignment and refinement (Ögmundarson et al. 2020).

Historically, separate ISO norms existed for each LCA phase, but were consolidated into ISO 14040:2006 and ISO 14044:2006. These standards provide comprehensive guidelines for conducting LCAs, emphasising principles such as transparency, consistency, and scientific integrity. ISO 14040 outlines general principles and requirements (International Standard ISO 14040:2006 2006), while ISO 14044 offers detailed guidance, including aspects such as critical review processes and reviewer competencies (International Standard ISO 14044:2006 2006). These norms were further supported by ISO 14071, which introduced additional criteria and guidance on critical review processes and reviewer competencies of LCA (International Standard ISO 14040:2006 2006; International Standard ISO 14044:2006 2006; International Standard ISO 14071: 2014).

2.2. Process modelling with subject orientation and PASS

The modelling or description approach chosen for this work is the paradigm of SO with its modelling language, PASS.

2.2.1. The paradigm of SO

The paradigm of SO as a dedicated approach to model processes was developed by Fleischmann (1994) and Fleischmann et al. (2012). In a nutshell, it is

> a modeling or description paradigm for processes that […] requires the explicit and continuous consideration of active entities within the bounds of a process as the conceptual center of description. Active entities (subjects) and passive elements (objects) must always be distinguished, and activities or tasks can only be described in the context of a subject. The interaction between subjects is of particular importance and must explicitly be described as the exchange of information that cannot be omitted (Elstermann 2019).

With this simple but effective concept, the paradigm is explicitly different from the classical approach of procedural or activity-oriented approaches that is predominant in other established standard modelling languages for process, such as the Business Process Model and Notation (BPMN) (Open Management Group, and OMG 2011) or Petri-Nets (Oberweis 1996). In theory, these modelling languages are already Turing complete meaning their expressiveness is powerful enough to describe any algorithm, or in our case process, imaginable. However, it is debatable how *good* in regard to their understandability such models can be for large, highly complex, real-life processes (Elstermann 2019).

2.2.2. The modelling language PASS

Where SO is the paradigm, the modelling language used is PASS. PASS embraces the paradigm of SO. A complete process model in PASS consists of multiple diagrams. The first is *Subject Interaction Diagram* (SID) as shown as a small example in Figure 2, as well as the main model later in Figure 6. SIDs show all active entities in a process, the subjects, as well as the messages or passive objects that these entities possibly can exchange in or during the process. The messages are represented by arrows that indicate the direction of transmission or reception. An important aspect to note is that while being the focus of a process model, the SID itself does not contain temporal information about when the messages are sent, only that they are exchanged.

For each *standard subjects*, such as the LCA-Project Coordinator in Figure 2, there exists a Subject Behavior Diagrams (SBD) that describe the individual, temporal sequence of activities for that subject in this process.

Figure 3 is the SBD for LCA-Project Coordinator with the three types of activities or *states* a subject can be in. Those are *Receive States* (red) that denote a waiting activity, *Send States* (green) that implicate an active communication activity (aka. sending of messages) with another subject, or *Do States* (yellow), which models the activities a subject does on its own. The arrows or transitions contain the conditions that must be fulfilled in order to leave one state for another. For example, a certain message (Msg.:) must have been sent or received or the Do-activity must have been finished.

In contrast to standard subjects, *Interface Subjects* do not have SBDs. They are used if a behaviour is unknown, modelled in another model, or, as is the case for this work, their behaviour is deemed of no greater relevance for a given process, e.g. because it is too simple. In effect, interface subjects are black boxes within a process but still with an active nature as any other subject. In the example of Figure 2, it is not really important how the management got the idea to initiate the LCA efforts and the process of how the various different LCA expert groups create their offers or when they would inquire about something that is simply unknown to the organisation to which this process belongs.

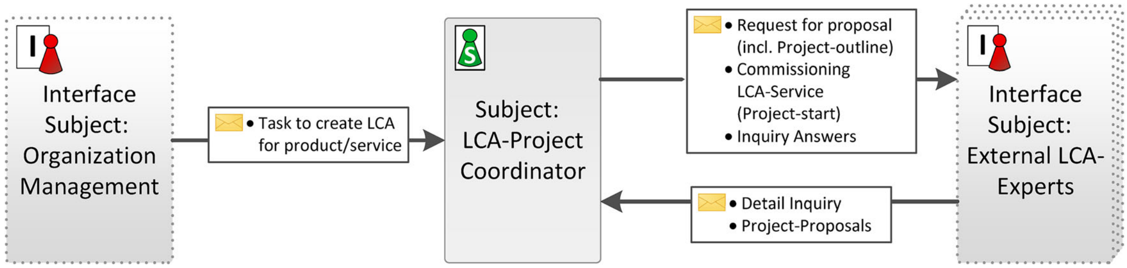

Figure 2. Example for a Subject-Interaction-Diagram of a PASS Process model: Starting and Consultant Hiring for LCA Projects.

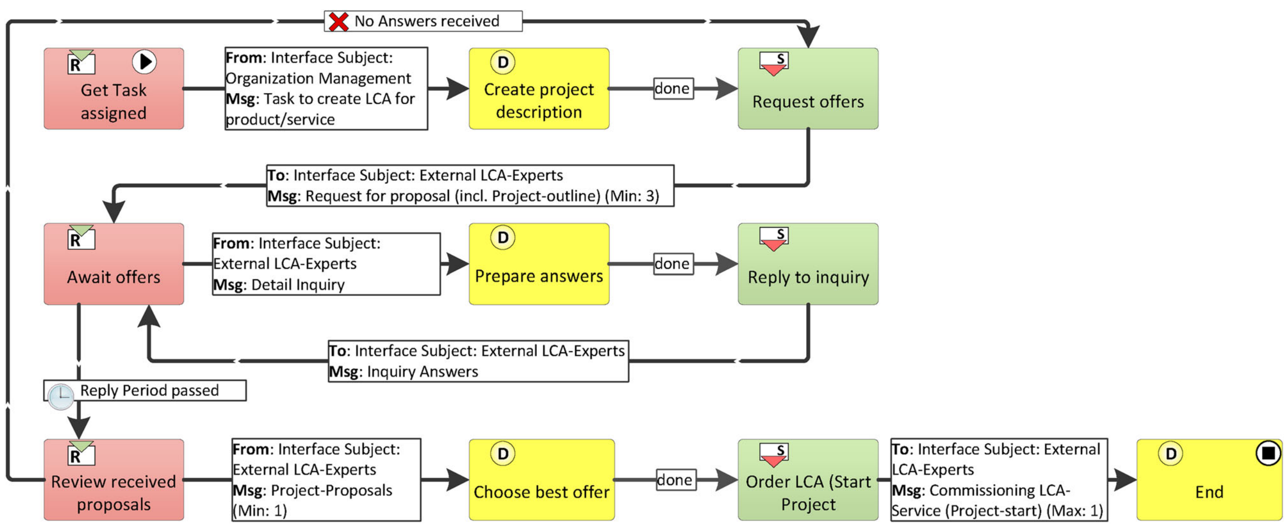

Figure 3. Example for a SBD of a PASS Process model – for the Subject LCA-Project Coordinator.

3. Related work

3.1. Resilient, human-centric, and sustainable manufacturing systems towards Industry 5.0

Industry 5.0 has emerged as a vision that complements Industry 4.0 by broadening its technical focus to include sustainability, human-centricity, and resilience in industrial systems (Cotta et al. 2021a). Rather than simply automating and optimising for profit, Industry 5.0 frames technology as an enabler for broader societal and environmental goals, a perspective that aligns with efforts to create systematic, transparent, and participatory methods of environmental assessment. In this context, an aspect repeatedly highlighted is the explicit need for structured methodologies that keep human stakeholders in the loop and allow for adaptability amid growing complexity and uncertainty (Grosse et al. 2023; Ivanov 2023). Several authors propose that blockchain-based smart contracts and decentralised control can bolster system robustness by eliminating single points of failure or data bottlenecks (Dolgui et al. 2020; Leng et al. 2023). Although these works are heavily focussed on supply chain disruptions or individualised manufacturing processes, their shared core principle, transparent, trustworthy coordination among multiple actors, also informs how we might organise environmental impact data more effectively in line with the ethos of Industry 5.0. Similarly, research on simulation platforms and digital twins underscores how real-time feedback loops improve both learning and decision making (Mourtzis 2020). Whether deployed in supply chain networks or production lines, the common thrust is a call for integrated, up-to-date information systems that help human operators contextualise disruptions, evaluate trade-offs, and reconfigure rapidly. Equally crucial is ensuring that these advanced infrastructures remain anchored in human values, an observation that appears throughout discussions of the transition from Industry 4.0 to Industry 5.0 (Grosse et al. 2023). Researchers stress that placing people at the centre of technological systems supports not only user acceptance but also genuine improvements in well-being. Efforts toward explainable AI architectures, for instance, reflect an increasing recognition that industrial data flows should be transparent and intelligible to a variety of stakeholders (Rozanec et al. 2023). The same principle applies in environmental assessments: if LCAs are carried out without clear delineation of responsibilities and data flows, confusion and mistrust can arise over how results are generated and interpreted. Against this backdrop, a human-centric modelling approach to LCAs represents one way to embody the broader objectives of Industry 5.0. By explicitly defining the role of each stakeholder, the data requirements they fulfil, and the logic behind decisions such as indicator selection or system boundaries, the LCA process gains clarity, trustworthiness and adaptability, characteristics that resonate with the robust, decentralised paradigms suggested by blockchain and AI-oriented frameworks (Dolgui et al. 2020; Leng et al. 2023). In addition, leveraging structured process models for LCAs aligns with calls for more resilient production: as soon as data gaps or methodological ambiguities are identified, roles and workflows can be quickly reconfigured, ensuring that the sustainability goals of the assessment remain intact (Ivanov 2023). Moreover, by integrating robust digital infrastructures such as advanced simulation tools (Mourtzis 2020) or metaverse-based collaboration platforms (Mourtzis et al. 2022), organisations can embed these human-centric LCA models into immersive or real-time training environments. This not only improves worker engagement and expertise, but can also help external stakeholders or customers visualise the environmental impacts of different production scenarios. As Industry 5.0 aspires to shape industrial transformation in ways that serve society, such transparent, highly accessible LCA models could become a cornerstone of widespread involvement and accountability in sustainable manufacturing. Ultimately, this approach builds on the collective insights of studies that have laid the conceptual and technological foundations for Industry 5.0.

3.2. Necessity of human-centred and structured LCA methods

Industry 5.0's emphasis on decentralisation, transparency, and human-centricity also challenges traditional LCA practices. Furthermore, exposing the limitations in the early design stages and the usability for non-experts leads to the need to explore structured, human-centred LCA methods that promise greater accessibility, flexibility, and relevance in sustainable decision-making.

Firstly, a structured LCA process ensures consistency and comparability between different assessments. This consistency is crucial when evaluating multiple products, processes, or systems, especially within industries that require a fair comparison of environmental impacts (Curran 2013). Furthermore, the accuracy and reliability of the results are greatly improved through a structured LCA process. By reducing the likelihood of errors, structuring ensures that the data used in the assessment are accurate and reliable. This reliability is essential to produce results that can be trusted by policymakers, industry leaders, and other stakeholders to guide strategic decisions (Rebitzer et al. 2004). In addition, a well-structured LCA process is more adaptable and flexible. It can be easily adjusted to different contexts or updated as new data or methodologies become available. This adaptability is vital to keep the assessment relevant over time, ensuring that it continues to provide valuable information in a rapidly changing environmental landscape (Guinée et al. 2011).

While structured LCA methodologies are foundational, they are not alone adequate for achieving effective LCA outcomes. By integrating human-centric approaches, the relevance and practical application of LCA in policy formulation and industrial practices can be significantly enhanced. Grubert (2017) highlights the need to incorporate subjective information, such as stakeholder preferences and risk attitudes, into LCA frameworks. This inclusion helps decision makers better understand and balance the trade-offs between environmental, social and economic outcomes, leading to more robust and socially acceptable decisions. In addition, several articles indicate that human-centred approaches to LCA can lead to improved outcomes. For example, incorporating stakeholder interpretation into the LCA methodology helps to apply results to practical decision making and increases acceptance of environmentally friendly road pavement alternatives (Osorto and Casagrande 2023). These human-centred approaches can also improve environmental outcomes and reduce impacts in waste management (Kavals and Gusca 2021) or rice production (Amirahmadi et al. 2022). Furthermore, human-centric models can serve as effective training tools in the realm of LCAs. For example, a study introduced an approach for multi-criteria environmental assessments of energy systems suitable for non-experts, given the complexity of conducting detailed LCAs (Douziech et al. 2021). Experts also highlight that human-centred models could improve training by improving the quality and reliability of results through the consideration of human decisions and interpretations, as demonstrated in a study of road restoration methods (Luvizão and Trichês 2023). Moreover, human-centred models offer opportunities to further develop LCA methodologies, such as better quantifying and integrating the impacts of the circular economy, emphasising user-friendliness and flexibility in the assessment of exposure scenarios (Egemose et al. 2022).

Furthermore, conventional LCA tools are typically used by specialised experts toward the end of product development, once detailed data is available. This timing is misaligned with the 'ecodesign paradox' – the fact that the greatest opportunity to reduce environmental impacts is in the early stages of design, when detailed data are lacking. As a result, many design decisions are made without LCA input, or LCA is only used for reporting rather than shaping the design (Chatty 2023). Additionally, novice or non-expert users often find existing LCA software cumbersome, with unfamiliar terminology and complex interfaces. These usability barriers mean that important stakeholders (such as product designers, engineers, or policy makers) may avoid using LCA tools, leaving sustainability considerations out of key decisions (Chatty 2023). Adopting a human-centred LCA approach addresses these gaps by making tools and processes more accessible, intuitive, and relevant to decision-makers. For example, a study evaluating user experiences with current LCA software found that most challenges 'emanate primarily from the shortcomings of the tools themselves' when applied in early-stage design contexts. In response, researchers have derived design recommendations (using insights from user interviews and principles of human-computer interaction) for new LCA tools tailored to early product development (Chatty et al. 2021). Such human-centred tools aim to provide quick, easy-to-understand feedback on environmental impacts with minimal required expertise, enabling early integration of sustainability.

3.3. Current research and research gap

While numerous studies and guidelines have extended LCA structuring beyond the ISO standards–with approaches ranging from differentiating detailed versus simplified LCAs (Guinée, Huppes, and Heijungs 2001) to best practices tailored for specific sectors such as wastewater treatment (Corominas et al. 2020), mechanical manufacturing (Cucchiella, Gastaldi, and Trosini 2017), 3D printing (Gebler, Schoot Uiterkamp, and Visser 2014), carbon capture (Müller et al. 2020), and social LCAs (Benoît Norris et al. 2020; Tokede and Traverso 2020)–persistent challenges remain. Literature reviews reveal critical inconsistencies in methodologies, poor data quality, inadequate uncertainty handling (Xie, Dong, and Zhao 2023), risks of overfitting due to sparse data (Maraden et al. 2023), and transparency issues linked to limited analyst expertise (Saade, Yahia, and Amor 2020).

Although recent efforts have integrated process modelling into LCAs, such as the development of process modelling tools (Mery et al. 2013) and multiobjective optimisation methods for eco-design (Ahmadi and Tiruta-Barna 2015), as well as proposals to incorporate process mining (Ortmeier et al. 2021), these initiatives primarily introduce new assessment methods rather than refining existing LCA practices. Moreover, they rarely utilise process models as educational tools to enhance practitioner understanding.

Figure 4 illustrates the key drivers behind our study. It juxtaposes Industry 5.0's emerging needs–such as human-centricity, sustainability, and collaborative ecosystems–with the ongoing challenges in LCA, including communication barriers, the 'ecodesign paradox,' and internal complexities. To fill this gap, our research pioneers the integration of subject-oriented process modelling with LCA.

Drawing on the proven effectiveness of the SO approach in complex domains like artificial intelligence (Elstermann et al. 2021) and digital twins (Bönsch et al. 2022), we develop a novel, human-centric reference model for LCAs. This model explicitly defines stakeholder roles, clarifies data generation and evaluation processes, and enhances transparency–thereby addressing the prevalent shortcomings in current LCA methodologies. By offering both a practical guide and an educational framework, our work facilitates improved application and interpretation of LCAs. Consequently, this study represents a crucial step toward standardising LCA practices and making them more accessible and reliable for both experts and non-experts.

4. Methodology

The research presented in this study adopted a comprehensive mixed-methods strategy to create and substantiate a subject-focussed reference model for Life Cycle Assessment (LCA). The rationale for selecting this mixed-methods approach stems from its ability to reinforce the model's toughness, adaptability, and practical significance. As depicted in Figure 5, this methodology integrated both deductive analysis and qualitative techniques aimed at the development and refinement of the model. The acknowledgment of deductive reasoning within qualitative research underscores the enhancement in the dependability of qualitative findings when subjected to systematic deductive methods (Hyde 2000). To validate the model, this multifaceted approach encompassed qualitative insights gathered from expert feedback in conjunction with a survey-based validation aimed at providing quantitative assessments.

The approach consisted of three main phases: initial model development, iterative model improvement, and model finalisation.

4.1. Initial model development via deductive analysis

The first phase involved a deductive analysis to create preliminary models based on existing literature on

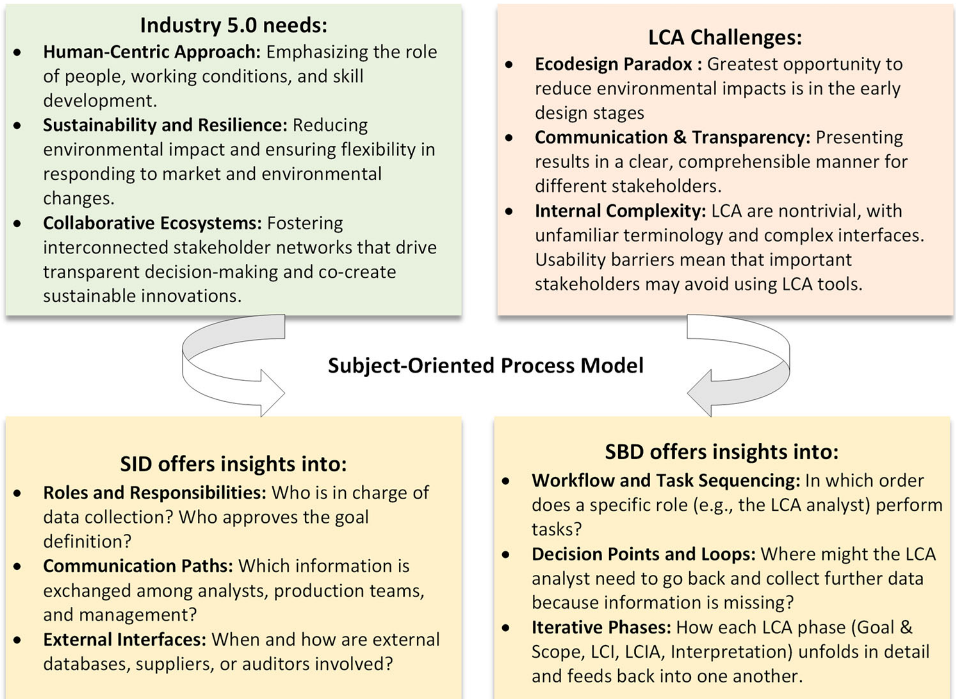

Figure 4. Summary of the Neceesity of the study.

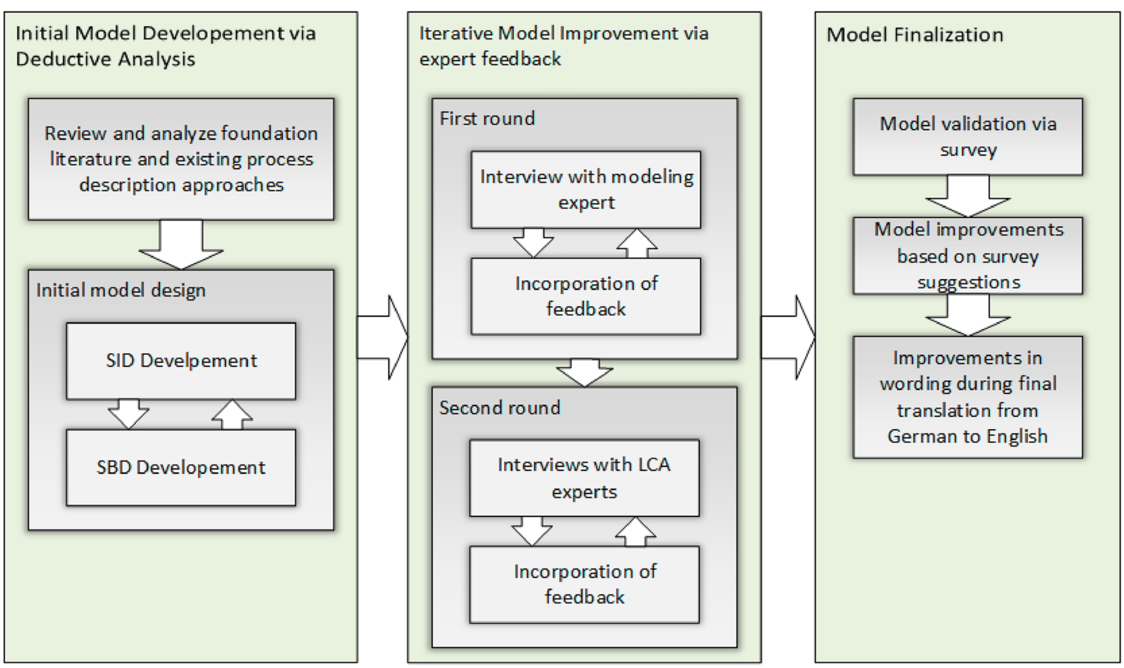

Figure 5. Methodological approach.

LCA procedures (Peterson and Jeanneret 2007). In a deductive literature research approach, the investigation commences with theoretical propositions that are developed from an extensive literature review. These propositions subsequently inform the data collection and analysis stages. This methodological approach ensures that the inquiry is consistently directed by a theoretical framework, thereby offering a structured method to empirically verify hypotheses with data obtained through the research. Crafting a research protocol that seamlessly incorporates suitable deductive strategies is essential for explanatory case studies, employing methods such as deductive thematic analysis and pattern matching, as noted by Pearse (2019). The role of conducting a thorough and systematic literature review is emphasised to maintain the integrity and reliability of research outcomes, by identifying various review types and establishing detailed guidelines for undertaking these reviews (Snyder 2019). This phase of deductive research aimed to establish a solid theoretical foundation and identify key components and interactions within the LCA process. Two primary models were developed:

(1) *SID*: This diagram outlined the interactions between various subjects (active entities) involved in the LCA process.
(2) *SBD*: This diagram detailed the sequence of activities for the LCA analyst, highlighting the central role in conducting LCA studies of this subject.

4.2. Iterative model improvement via expert feedback

The second phase included iterative rounds of feedback, expert consensus, and systematic refinement, to enhance the initial models through structured expert input (Crisp et al. 1997). Qualitative methodologies, including focus groups and expert interviews, offer an abundance of rich, detailed insights and thoroughly developed perspectives. Despite their less rigorous statistical foundation and potentially limited generalizability, they were selected in this study owing to the specific goal of developing and refining a model. The decision was further influenced by the scarcity of individuals possessing expertise in both Life Cycle Assessment (LCA) and Predictive Analytics for Sustainable Systems (PASS) (Hyett, Kenny, and Dickson-Swift 2014).

This phase included two rounds of expert interviews: In the first round, the preliminary models were presented to two PASS modelling specialists with 5–10 years of experience in PASS. Feedback focussed on improving the methodological aspects, addressing modelling errors, and improving the formal syntax of the models.

In the subsequent round, the refined models were then reviewed by three LCA experts, with at least 3 years of experience in conducting LCAs. Feedback in this round concentrated on the completeness and clarity of the information, with suggestions for further refinement. This round was conducted twice to ensure thorough examination and consensus. Each expert was separately interviewed, during which the model was presented and potential problems and gaps were discussed.

4.3. Model finalisation

In order to enhance the validation process of the model and to provide a comprehensive quantification of the results, it is crucial to implement a quantitative methodology. Utilizing survey-based quantitative techniques enables the collection of extensive datasets from a diverse group of respondents, which facilitates a rigorous statistical examination. However, while such approaches are advantageous for their scope and statistical strength, they often fall short in capturing the subtle and nuanced insights that are crucial for the intricacies of sophisticated models, such as those implemented in Life Cycle Assessment (LCA) (Yin 2013). Consequently, the ultimate stage of the research comprised a meticulously structured multi-step protocol aimed at validating and further refining the models, ensuring a thorough and precise enhancement of their accuracy and applicability:

A comprehensive survey was executed to explore a variety of subjects, primarily focussing on the overall comprehensibility of the model under investigation. Additionally, the survey compared this model with traditional Life Cycle Assessment (LCA) models and evaluated it in alignment with the standards outlined by DIN ISO 14040 and ISO 14044. The objective of the survey was to gauge both LCA experts' and the general public's understanding and applicability of the models. In terms of methodology, the survey encompassed a heterogeneous sample size consisting of 20 participants with distinct backgrounds and varying degrees of expertise. This cohort included four professionals with significant involvement in the LCA sector as well as 16 individuals without prior exposure to LCA methodologies. The expert participants were meticulously chosen based on their direct experience in LCA research and practice, whereas the group of laypeople was randomly assembled to mirror potential novel users of the model from a broad range of domains, including but not limited to students and employees in various industrial sectors.

The survey served a dual function: initially, it contributed to the refinement of the model by incorporating additional expert feedback. At the same time, the objective was to validate the current state of the model and assess its comprehensibility, exploring whether it can effectively introduce the subject matter to novices.

Before the questions, key LCA terms were introduced with descriptions and examples, including: LCA, Primary Data, Secondary Data, Generic Data, Inventory Analysis, Allocation, Cascades, Impact Assessment, Impact Indicators, Characterization Factor, Characterization Model and Impact Endpoints.

The survey aims at a diverse audience, including LCA experts and laypeople, which requires different questionnaires due to different levels of knowledge on LCA-specific questions. The questionnaire for both groups began with demographic questions, including questions about age, education level, occupation, and experience with LCA and modelling in PASS. These questions are formulated on the basis of experiential knowledge. The questions about feedback on the model were divided into four subsections. First, participants were asked about the general comprehensibility and clarity of the model. Second, LCA-specific questions about the model were asked. Third, participants were asked about the potential for future reuse of the model. Fourth, the survey was concluded with general questions about the importance of LCA. LCA focussed questions differ between laypeople and experts. Laypeople compared the model with the standard LCA model (see Figure 1), while experts evaluated the models' compliance with the DIN standards ISO 14040 and ISO 14044. Subsequent questions for both groups explored potential applications of the model in order to assess whether it could effectively introduce unfamiliar individuals to the subject. The final questions addressed general opinions on the utility of LCAs.

The survey was conducted using a 4-point Likert scale to minimise neutral responses (Likert 1932). During it, the participants had the option to comment on the model and give suggestions for improvement, which were incorporated afterwards. Feedback from the survey was aggregated to consolidate similar points and facilitate the refinement of the model. Feedback from the survey was used to make final adjustments to the models, ensuring that they met the needs and expectations of both expert and non-expert users.

5. Results

In the following section, we present the SO models developed for the LCA process within organisations. The models focus primarily on the cradle-to-gate LCA, as it involves the collection of primary data only from within the organisation, without extending to the use and end-of-life stages. It is the final version of the model, after including all the suggestions and recommendations of the expert feedback and the survey.

5.1. Communication flows and stakeholders in the LCA process

In the SID (see Figure 6) of the process model, nine subjects are identified. In the centre of the diagram is the LCA analyst (green) around whom the LCA process revolves. In addition, three coloured areas are visible, which symbolise thematic groups. These are subject groups and the subjects included are interface subjects. All subjects are labelled with comment boxes (light gray), which contain a definition of the respective subject. Above the LCA analyst, the subjects of the LCA software systems are grouped. The subjects shown there are the external databases and the LCA software operated by the analyst. Below the analyst, the subjects of the company that wants to perform an LCA are grouped (yellow). The subjects involved are the person responsible for the LCA, the production of the product in question, and a data manager. The purple box at the bottom of the diagram shows the external stakeholders, including the public, independent reviewers, and external production facilities.

In a typical scenario, the person responsible for the company, who is assigned to perform an LCA but does not have the required expertise, sends a request to the LCA analyst who may also be associated with the same company. If the analyst accepts the request, the two parties jointly determine the required goals and the scope of the LCA. During the LCI, the LCA analyst will collect data. The analyst requests primary data from the person responsible in the company. If primary data are not available, the responsible person will be informed by the organisation data controller, who approaches the production department to obtain measurement data. In addition, the LCA analyst searches external databases for secondary data. These databases can usually be called up directly in the LCA software, which means that, unlike the primary data, these data do not have to be uploaded separately by the LCA analyst. The analyst needs to contact the production department to find out whether it uses or passes on recycled materials. If necessary, the external production departments are also questioned. All data collected are transmitted to the software. When data gathering is completed, the LCA analyst can start the data aggregation process in the LCA software. Afterwards he receives the LCI results. After the necessary characteristics are set for the LCIA, the software sends the results of the LCIA. The analyst can send interim reports and the final results, including documentation, to the responsible person in the company. The responsible person forwards these results to independent reviewers who provide feedback and validate the process by reviewing the documentation. The results and reviews can then be presented to the public.

5.2. Workflow and decision-making of the LCA analyst

Of particular interest is the behaviour of the LCA analyst, shown in Figure 7.

The SBD is divided into four coloured task areas: the definition of goal and scope (yellow), the LCI (orange), the LCIA (green) and the interpretation (purple). These

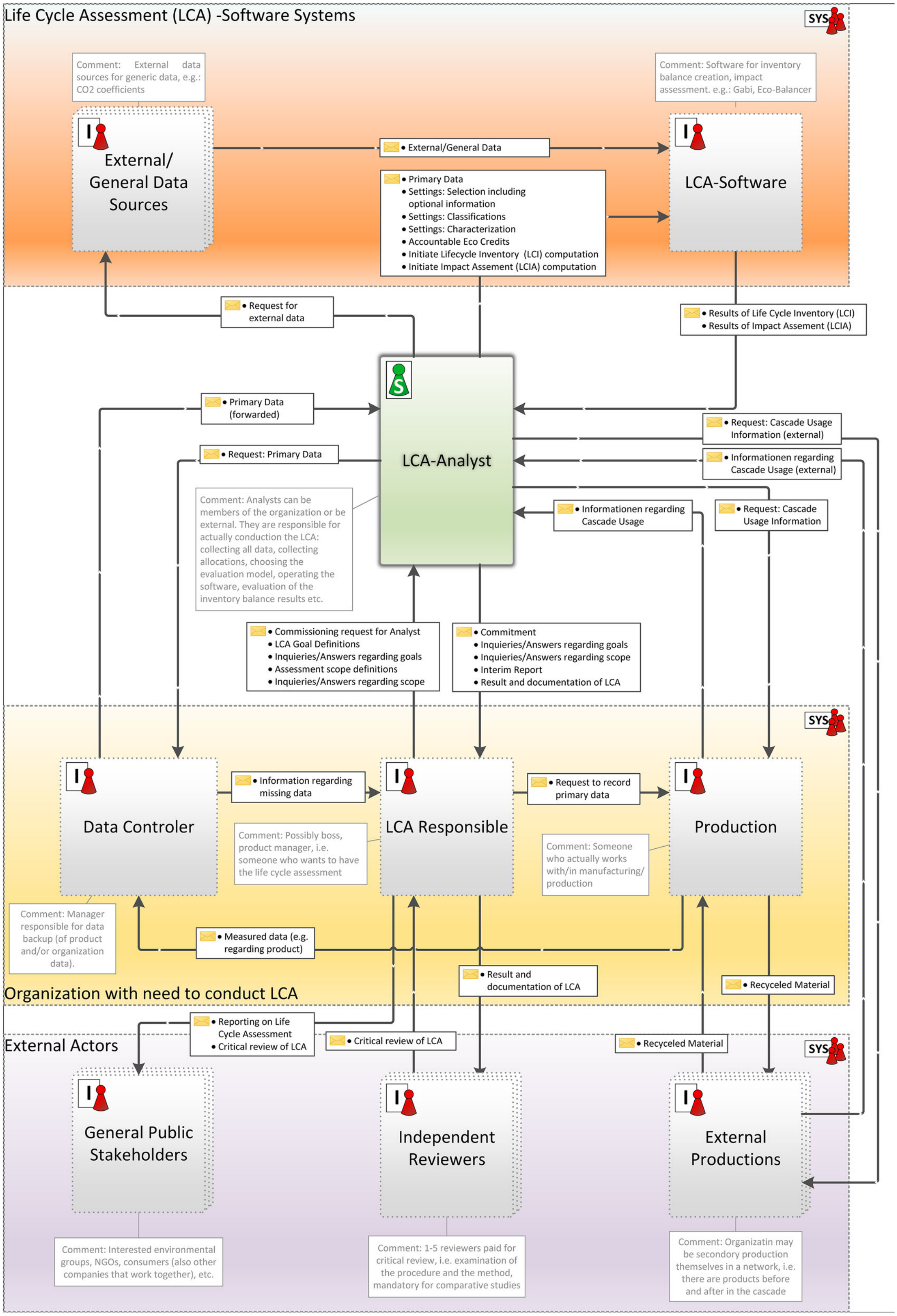

Figure 6. SID representing stakeholder interactions in the LCA process.

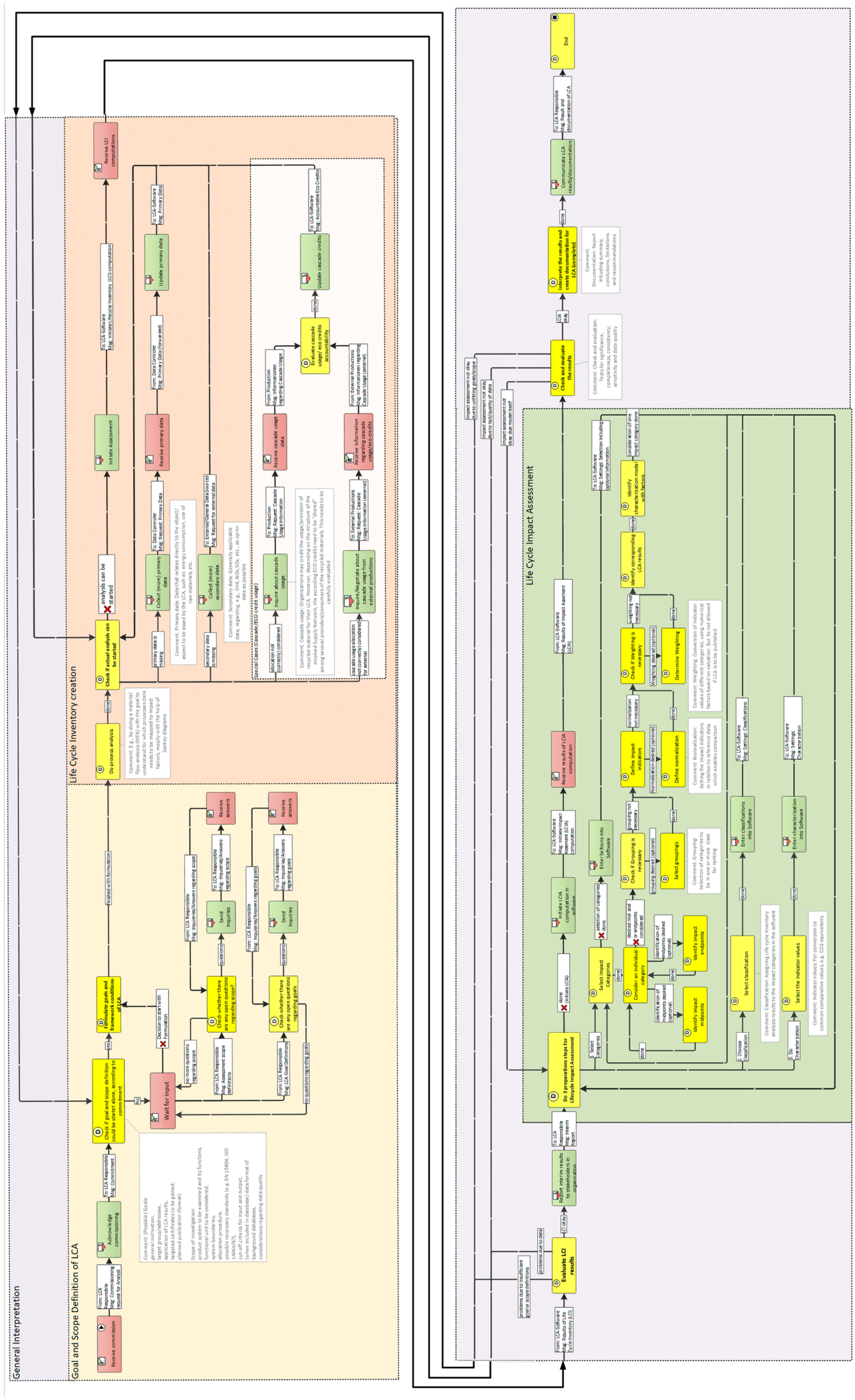

Figure 7. SBD of the LCA Analyst.

correspond to the four phases of an LCA and are coloured the same as in Figure 1.

5.2.1. Goal and scope definition

The work process of the LCA analyst starts with the receipt of the commission request from the person responsible for LCAs within the company. For the goal and scope definition the analyst can work on its own or with the responsible person, in the second case close communication between both is necessary, represented through the loops from send and receive states. During the definition of the goal and scope, it is important to state the underlying use case for conducting the study to clarify the value and significance of the results. In addition, the motivation for conducting the LCA study should be stated, e.g. to respond to a market development or to fill a research gap. Furthermore, the target audience or user group of the LCA study must be specified to ensure that the results have relevant application areas and provide value. For example, this could include management, potential customers, or other researchers. Finally, it is important to describe whether the publication of results is planned, taking into account the form and content of the statements, including comparison statements between products. The scope of the LCA study should be carefully defined. This includes several important aspects: First, the product system must be chosen, as well as the functions of the system or, in the case of comparative studies, of the systems. Other relevant aspects of the scope of an LCA study are the definition of a functional unit and the boundaries of the system. The choice of allocation procedure, the method for impact assessment and impact categories, as well as methods for evaluation and data requirements, need to be evaluated. In addition, assumptions, values, and optional components, limitations, and requirements for data quality should be considered. The cut-off criteria for input- and output data should be defined. The type of critical review, if applicable, and the type and structure of the report should also be defined.

5.2.2. Inventory analysis

The second task area involves creating an inventory of all the inputs and outputs of a product or process. This task area begins with a process plan that may include material flow analysis (MFA). The integration of LCA and MFA provides a more complete system understanding in that, on the one hand, the regional system is investigated with the MFA and, on the other hand, every process, including the supply chain beyond the regional boundaries, is well understood (Rochat et al. 2013). After that, data are collected until the LCA analyst decides that all necessary data are uploaded to the software so that the balancing can start. This decision to end the data collection and to leave this state is indicated in the SBD through a red 'X', the user cancel. Data to be collected by the LCA analyst, visualised by send states, are primary and secondary data. Primary data is to be uploaded to the software, and secondary data is directly integrated by means of a database. In special cases (white topic box), the LCA analyst must also request cascade usage internally and then externally. After receiving this information, the LCA analyst calculates credits if necessary, which are also entered into the software.

5.2.3. Life cycle impact assessment

The third task area of LCA, involves characterising and evaluating the potential environmental impacts of the significant inputs and outputs identified from the inventory analysis. In The SBD we see a Do-state, which can be left by means of a user-cancel. This state is for the execution of the three preparatory steps for the impact assessment. In the first preparatory step, the analyst has to *'Select Categories'*. Impact categories are selected, whereby most of the time a standardised set of impact categories is used, which means that the deposited characterisation model, etc. is already determined. Otherwise, for each impact category, impact mid- and/or endpoints are identified, which can be grouped if desired. Impact indicators are defined and there is the option for normalisation and also for weighting. Subsequently, the associated LCI results and characterisation models and factors can be identified. The process can continue when the selection of all impact categories is completed. The data collected are then entered into the software. In the second preparatory step, he has to *'Select Classification'*, the classification must be selected or entered in the software. This means that LCI results are assigned to the impact categories. *'Do Characterization'* is the third preparatory step; indicator values are selected in the software, for example, for the conversion of the data into CO2 equivalents.

After these preparatory steps, the LCIA is started in the software, from which the LCA analyst receives the results.

5.2.4. Interpretation

The activities in the following are part of the interpretation task area, in which various results are reviewed and verified for accuracy. If discrepancies or problems are identified, loops can be initiated, leading back to the previous task areas for further investigation and resolution. If the results are acceptable, the process is continued. After receiving the LCI and LCIA results, the LCA analyst must thoroughly review them. This review process is a critical step in the interpretation phase, where the analyst assesses the significance of the identified environmental impacts, checks for consistency and sensitivity, and evaluates the robustness of the results. If the results do not align with the original goal and scope of the LCA, or if significant uncertainties are identified, the LCA analyst may need to repeat data collection, adjust the goal and scope definition, or refine the methodological choices to ensure the accuracy and reliability of the results (Laurent et al. 2020). The interpretation phase also involves identifying trade-offs between different environmental impacts and determining the most sustainable options, which may require complex value judgments considering the specific context and priorities of the stakeholders involved (Ciroth 2017). If the results are robust and consistent, the process proceeds. After validation, the LCA analyst prepares the interpretation, including notes on the balance sheet that clearly communicate the findings, implications, and any limitations of the study. Effective communication is essential to ensure that results are understandable and actionable for decision makers within the company. Finally, the LCA analyst concludes the process by sending all the data collected, including the final results, documentation, evaluation, and recommendations, to the responsible person in the company. These recommendations may include suggestions for further investigation, improvements in the product or process, or strategic actions to improve environmental performance (Sala et al. 2020).

6. Validation

The validation is divided into the topic of syntactical validation and the content validation through the survey.

6.1. Syntactical validation

Since PASS is a formal process modelling language, it was possible to verify its syntactical correctness using the tool built into the editor used, which is based on a simple simulation approach.

6.2. Content validation

The survey for the content validation involved a diverse group of 20 individuals with varying backgrounds and levels of expertise. This included four professionals in the field of LCA, as well as 16 laypeople with no prior experience in LCA. A summary of demographic data is presented in Figure 8.

The mean age of participants hovered around 30 years. Approximately 80 percent of respondents possessed an education level exceeding A-levels. In terms of professional disciplines, environmental science, engineering, and other scientific fields were represented by 20 percent, 25 percent, and 30 percent of participants, respectively.

A summary of the level of experience is presented in Figure 9.

Regarding the LCA experience, experts demonstrated a greater engagement compared to laypeople, with only four laypeople exhibiting preexisting familiarity with the topic. The experts have conducted a minimum of one LCA, one expert has also conducted more than five LCAs. In contrast, the laypeople showed more proficiency in PASS modelling.

6.2.1. Results of the survey

Figure 10 shows the results of the survey about the content validation. Each histogram separately illustrates expert and layperson responses, symbolising diverse thematic blocks, such as model in general or LCA specific questions.

Description of the sample

a) Age

	Min.	Max.	Mean.	Std.
Laymen	19	59	31	10
Experts	25	40	30	6

b) Education level **c) Professional field**

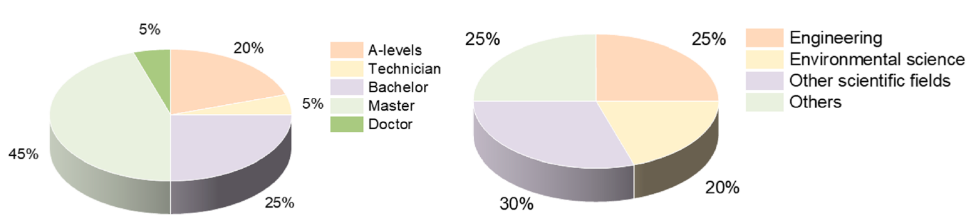

Figure 8. Diagrams for the demographic data of the participants of the *survey*: (a) age, (b) level of education and (c) professional field.

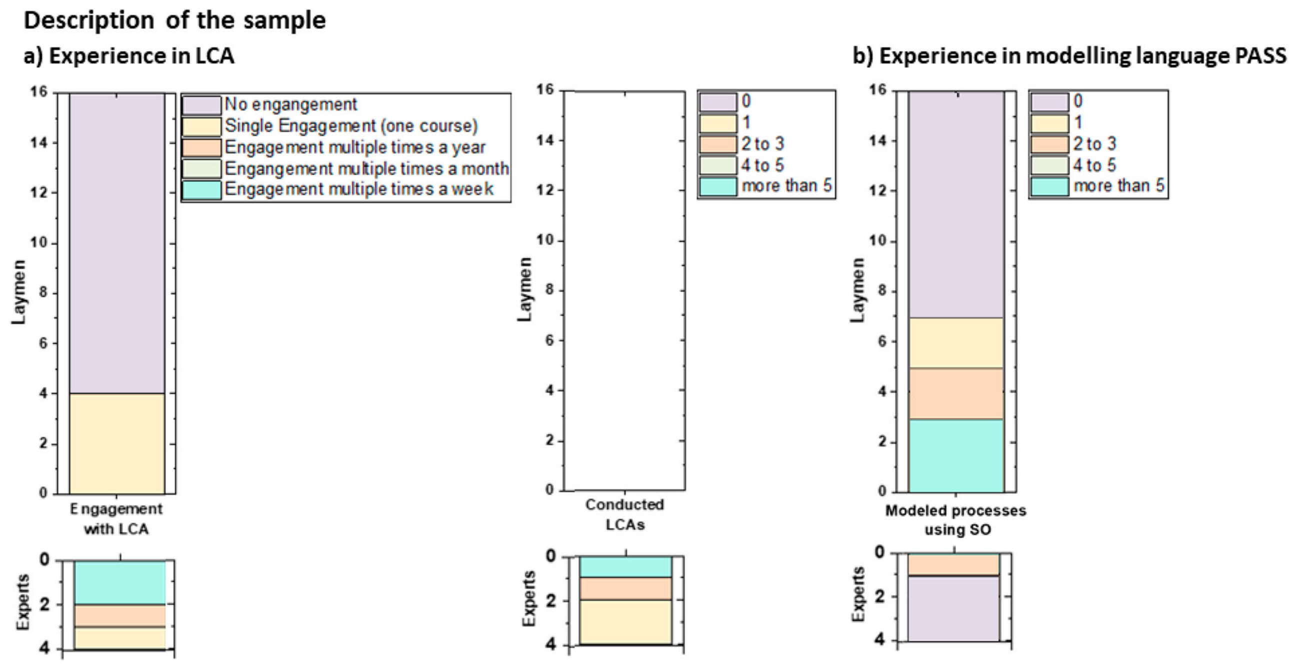

Figure 9. Diagrams for the experience level of the participants of the *survey*: (a) experience in the topic of LCA, (b) experience in the topic of PASS.

In the following the responses to each topic for laymen and experts seperately will be displayed:

(a) Model in General

Laymen: The majority of laymen rated the clarity of language between scores 2 and 3, reflecting general satisfaction but also highlighting some room for improvement. For the organisation of content, scores were distributed across all levels, with a tendency towards higher scores, suggesting that while the content organisation is generally good, improvements can be made. The real-life relevance of the model was primarily rated as 3, indicating that laymen found it quite satisfactory. The focus on tasks received mixed scores, implying that while some participants found the focus appropriate, others identified areas for improvement. The adaptability of the model also received a range of scores, with a slight leaning towards higher ratings, signifying that laymen generally found the model to be adaptable but still see room for improvement.

Experts: Expert ratings were more consistent and generally higher across all criteria compared to laymen, indicating that experts found the model clearer, better organised, more relevant, task-focussed, and adaptable. However, adaptability, while rated high, still has some room for refinement, as indicated by the distribution of scores.

(b) LCA Specific Questions

Laymen: In terms of the model's ability to clarify LCA, the majority of laymen gave scores of 3 or 4, indicating that they found the model effective in clarifying LCA concepts. The model's illustration received mixed but generally high scores, with a majority rating it positively. The comparison of the model with LCA questions also showed a majority rating of 3, suggesting that the model effectively represented LCA questions. High scores were given for the model's ability to answer LCA questions, indicating that laymen found the answers provided by the model satisfactory. Similarly, the model's guidance for LCA processes was rated highly, demonstrating its perceived effectiveness in this area.

Experts: Experts rated the model's compliance with ISO 14040/44 standards predominantly high, reflecting adherence to these standards, despite one instance of a score of 0. The relevance of the LCA aspects covered by the model also received high ratings, indicating that experts found the relevant aspects well covered. Proper arrangement of LCA aspects received mixed ratings, including one score of 0, but generally remained high, showing satisfaction with the arrangement. The appropriateness of the model size was also rated highly, indicating satisfaction among experts.

(c) Potential Reuse of the Model

Laymen: The potential for future reuse of the model was largely rated high by laymen, reflecting a strong belief in its utility for future applications. The introduction of the model for beginners received mixed ratings, though many gave it high scores, indicating that while the model is useful for beginners, there might be areas that require enhancement for this particular audience.

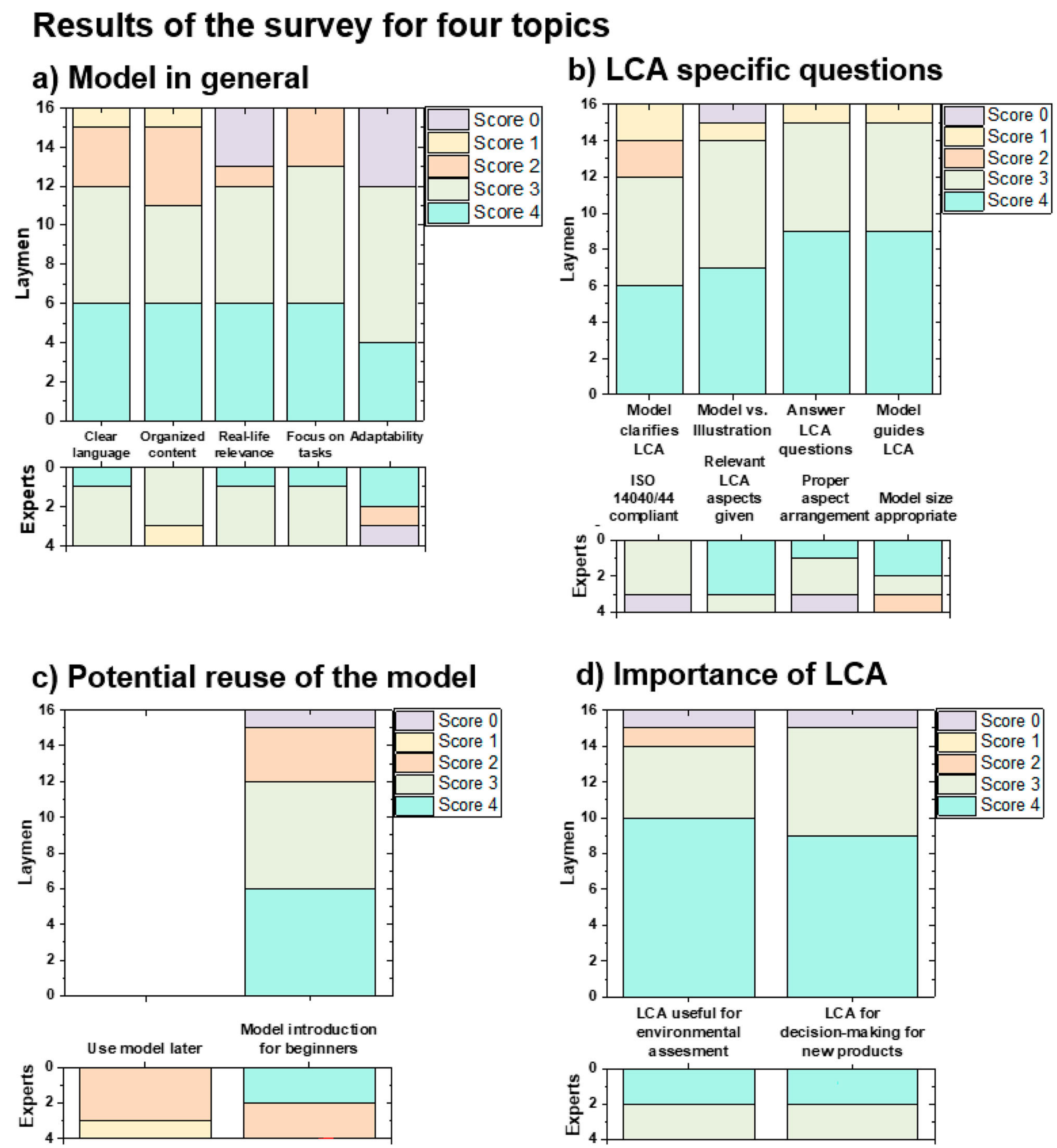

Figure 10. Diagram for the results of the *survey* for general comprehensibility and clarity of the model.

Experts: Experts showed varied responses but generally indicated potential for model reuse, particularly for introducing the model to beginners, though there are some areas identified for improvement.

(d) Importance of LCA

Laymen: Laymen rated the usefulness of LCA for environmental assessment primarily with scores of 3 and 4, underscoring a strong belief in its utility. The importance of LCA for decision-making in new products was similarly rated highly, indicating that laymen perceive LCA as critical in decision-making processes. However, there were a few outliers who rated these aspects lower.

Experts: Experts mirrored the views of laymen but with slightly higher consensus and higher scores overall, reflecting strong agreement on the importance of LCA for both environmental assessment and decision-making in product development.

7. Discussion

The Discussion section is subdivided into different subsections for clarity. The initial motivation for this paper came from the needs of Industry 5.0. As stated in Figure 4, human-centric approaches are one of them. To address that need, we considered the use of SO for the process model, based on several reasons, which will be highlighted in Subsection 7.1. Another need of Industry 5.0 is the reduction of environmental impacts, which could be done by first assessing the impact, through, for example, LCA, and acting on the results. Therefore, a model of the LCA process in particular was constructed. The general implications revealed through the SO process model, which is trying to address the challenges of LCA, are discussed in Section 7.2. The topics of the subsection are the presence of various stakeholders involved in the process, addressing the need of I 5.0 for collaborative ecosystems, and the internal complexity of LCAs, with its iterative nature, and the fact that the reliability and consistency of LCAs are crucial for their effectiveness. The challenge of communication and transparency is also addressed. Sections 7.3 and 7.4 will discuss possible application scenarios of the model and the actual usability of it. The last subsection discusses the limitations of the given methodology.

7.1. *Justification of the SO approach as human-centred approach*

SO was chosen primarily because it facilitates the inclusion of human factors and allows detailed descriptions of human-centred systems. Simultaneously, it facilitates the integration of both technical and organisational components within a model, while the use of validation tools in PASS improves the quality of models by enforcing syntactic rules, which aids in the development of strong, accurate, and formal models. The primary hypothesis is that the potential human-centeredness originates from the fundamental nature of PASS. The existence of the SID forces a general reconsideration of what ‘a process’ is. In classical considerations, ‘a process’ is often seen as ‘a collection of tasks/activities’, following the concept of input-task-output (Elstermann 2019). SO/PASS from the beginning forces a user to describe a process as what it most likely is in reality – a sociotechnical *system*. In PASS, initially, active entities within an SID must be identified within a specific process context. While it is still possible to not include humans in such a description, it is nearly impossible to describe processes that involve them without mentioning them explicitly as subjects and having only as the data source for technical systems. The identified active participants in the SID include the LCA-Analyst, Data Controller, LCA Responsible, both internal and external production personnel, general public stakeholders, and independent reviewers. Many of these aspects can also be achieved with other modelling languages, but SO/PASS naturally encourages the asking of certain questions that are otherwise left to chance. Examples of these questions are ‘Who/what initiates an exchange?’ ‘Where does a request/instruction come from?’ or ’What do I need to do?’ – followed by ‘Why do I have to do this?’ – It is then necessary to analyze the answers to these questions and present them in detail in the model. In PASS, therefore, at least the origin and destination of the information must be named by including (at least) the corresponding (interface) subject, which in turn could be a human. Furthermore, a model reader can easily find her or his role in the model with clear role definition, consequently leading to improved explainability. In summary, by framing LCAs as a sociotechnical process, one that relies on transparent role assignment, iterative refinement, and stakeholder collaboration, we incorporate sustainability, human-centric design, and resilience into a single methodological template. This integration not only reflects the paradigm shifts advocated by Industry 5.0 (Cotta et al. 2021a; Grosse et al. 2023) but also offers a concrete application to bridge advanced digital technologies with clear social and ecological objectives.

7.2. *General implications to the topic of LCA through SO*

Through a subject-oriented analysis of the LCA process, several implications are identified.

First, although the LCA analyst is at the centre, there are many actors involved in the LCA process who can all influence the results. The presence of various individual stakeholders, including NGOs, media and government bodies, in the LCA process cannot be understated. These stakeholders shape the outcomes of LCAs by introducing diverse perspectives, pressures, and expectations. For example, NGOs can advocate for stricter environmental standards and media coverage can shift public opinion, leading to an increased demand for sustainable practices. The SID effectively maps out and visualises these interactions, demonstrating the intricate web of influences that an LCA analyst must navigate.

Second, the reliability and consistency of LCAs are crucial for their effectiveness. The complexity observed in the SBD raises concerns about the comparability of results, particularly when different analysts are involved. The subject-oriented reference model offers a pathway toward standardisation by providing a structured framework that guides analysts through the LCA process. This approach can reduce subjective variations by prescribing specific steps and interactions, which is especially beneficial in contexts where comparative LCAs are required, such as product certifications or regulatory compliance assessments.

In addition, leveraging structured process models for LCAs aligns with calls for more resilient production: as soon as data gaps or methodological ambiguities are identified, roles and workflows can be quickly reconfigured, ensuring that the sustainability goals of the assessment remain intact (Ivanov 2023). Specifically, this could be achieved through digital workflow platforms or digital twins, where predefined roles, responsibilities, and process sequences can be dynamically adjusted in real time. For example, if specific data inputs for an LCA become unavailable, structured models could automatically identify alternative data sources or prompt human intervention for validation, thereby maintaining the robustness and continuity of the sustainability evaluation. However, our current approach primarily addresses resilience through reconfigurable design and human-centric decision-making, leaving other important dimensions of resilience, such as decentralised autonomous management and system redundancy, less explored. For example, decentralised autonomous management could be implemented by distributing decision-making power across multiple stakeholders or local assessment nodes, ensuring continuity even if central decision structures fail or become compromised. Similarly, incorporating redundancy through parallel or overlapping data streams and assessment pathways would provide backup options in case of primary system failures or data disruptions, further enhancing overall system resilience. Future research should explicitly investigate how these additional resilience dimensions can be integrated into human-centric LCA models.

Third, the iterative nature of the LCA process, as highlighted by the SBD, underscores the time-consuming and labour-intensive aspects of conducting a full LCA. In certain applications, such as the early stages of product development, faster and more approximate methods may be necessary. An Artificial Intelligence (AI) approach, for example, could be employed to generate preliminary LCA results, enabling quicker decision-making and early steps toward sustainability. This is particularly valuable when complete data are not yet available, allowing companies to initiate environmentally friendly practices from the outset. Furthermore, crucial factors are usually determined at the beginning of the process (Mami et al. 2017).

Fourth, the subject-oriented analysis highlights the critical role of communication and knowledge exchange among all participants of the process, here called stakeholders, throughout the LCA process. Effective communication is essential to bridge the gap between the technical details of the LCA findings and the understanding of various stakeholders to ensure that these findings are properly considered in decision-making processes. This transparency fosters trust and encourages active participation, which can lead to more accurate and widely accepted LCA outcomes. At different stages of the LCA process, specific stakeholders should be actively involved to ensure the success of the assessment. Company management should participate early in the Goal and Scope Definition phase. Their participation ensures that the LCA aligns with the company's strategic objectives and that the goals of the assessment are clear and relevant. By contributing to the definition of the scope of the study, management helps set the functional units, system boundaries, and allocation procedures, which are critical to the LCA's accuracy and applicability. During the LCI phase, production teams play a vital role. These teams provide the primary data necessary for the LCA, including details on materials, energy consumption, and waste generation. Their direct involvement ensures that the data collected are accurate and reflect real-world practices, which is essential for producing credible LCA results. Data managers are key stakeholders during both the LCI and LCIA phases. Their responsibility is to ensure that all data is correctly managed, stored, and processed. This role is particularly important when integrating secondary data from external databases or ensuring compliance with data management regulations. Their participation helps maintain data integrity throughout the LCA process, which is crucial to the reliability of the final results. External stakeholders, including NGOs, regulatory bodies, and independent reviewers, should be involved at multiple points, especially during the Interpretation phase and during any Critical Reviews. NGOs and regulatory bodies offer valuable information on the environmental and social impacts of the LCA, helping to align the results with broader sustainability goals and regulatory requirements. Independent reviewers, in turn, provide an essential function by validating the LCA, ensuring that the methodology and conclusions are sound and credible. Finally, although the public and consumers may not be directly involved in the technical aspects of the LCA, their input becomes important during the Reporting and Communication phase. Engaging these stakeholders through transparent reporting or public workshops can improve the acceptance and impact of the LCA findings. Public feedback can also influence future LCAs by highlighting areas of interest or concern, ensuring that assessments remain relevant and aligned with societal expectations. The SID can explicitly map out these communication links, illustrating how information flows between the LCA analyst, management, production teams, data managers, and external actors. For example, the SID could show how data requests are made to production teams, how findings are communicated back to management, and how external reviewers provide feedback on the results. By clearly defining these communication pathways, the SID ensures that all stakeholders are engaged at the appropriate stages, leading to a more coordinated and effective LCA process.

Fifth, the adaptability of LCA methodologies to emerging technologies and practices is crucial. As industries evolve and new technologies emerge, traditional LCA methodologies could face limitations to capture the full environmental impacts of innovations, such as advanced materials, renewable energy sources, or new manufacturing techniques. This requires the ongoing development of LCA methods that can adapt and accurately assess the environmental footprints of cutting-edge technologies. The subject-oriented reference model can facilitate this adaptation by providing a framework that emphasises the roles and perspectives of different actors involved in the development and implementation of new technologies. The roles are emphasised in the SID, where their correspondence to larger groups is illustrated along with the interaction exchanges between various subjects. For example, if new regulations are introduced regarding data management, the SID allows for clear identification that the Data Controller is principally affected. Along with the production, from which the data first reaches the Data Controller. Furthermore, new regulations are likely to alter the way primary data are requested and transferred to the LCA analyst.

7.3. Possible application scenarios of the model of the LCA process

Subject-oriented process models for LCAs offer an array of application scenarios in both research and industrial practice. Unlike traditional LCA guidelines, whose main focus lies in cataloging inputs, outputs, and impact pathways, the subject-oriented approach foregrounds the human dimension and the flow of information among stakeholders. This human-centred perspective not only clarifies the responsibilities, but also strengthens the data quality and transparency of the processes. In an educational context, subject-oriented models can serve as a powerful tool for instructors and corporate trainers alike. By highlighting the roles and actions of individuals – rather than simply listing the tasks required to complete an LCA – these models improve the grasp of learners of how data and decisions flow through an organisation. In academic settings, for example, novices often struggle to see how theory translates into real-world applications. The SID and the SBDs offer an intuitive visualisation: they break down the LCA process step by step, showing who collects data, who verifies it, and who ultimately interprets the results. This clarity benefits students who can walk through each phase of an LCA in a structured manner, and it benefits newcomers in companies who quickly learn which department or role to contact for the inputs they need. Beyond education, subject-oriented models also encourage interdisciplinary collaboration. LCA by its nature spans engineering, chemistry, environmental science, and organisational decision making. Because subject-oriented diagrams explicitly map out the communication channels – who speaks to whom, about what, and when - project teams gain a blueprint for collaboration. This framework reduces the risk of miscommunication, especially in complex settings where multiple stakeholders (from production and data management to marketing and external suppliers) must coordinate to ensure consistent inventory data and aligned assumptions. In this sense, the models function like a map showing the path of each traveller and the points at which those paths intersect. As industrial settings become increasingly complex and many companies seek to scale and adapt LCAs across multiple product lines and supply chains, subject-oriented models provide a template that can be replicated and modified as necessary. Rather than building each LCA approach from scratch, organisations can import the same basic subject-structure: production teams, data controllers, analysts, external data providers, and simply adapt it to the unique requirements of a new product or a different geographical region. In a circular economy context, where collaborations can span across numerous entities that reuse, recycle, or reuse materials, these models also make it easier to see how information and materials travel from one organisation to the next, helping to maintain consistency in impact assessments. All of these scenarios benefit from the deeper scientific and methodological strengths of the subject-oriented paradigm. Insisting on the explicit definition of 'active entities' (the subjects) and their interactions, the approach ensures that human decisions and organisational structures are not overlooked. This makes the resulting LCA more transparent, more easily audited, and more amenable to iterative improvement. With each step of an LCA: definition of goals and scope, inventory data collection, impact assessment, and interpretation, subject-oriented models spell out who is responsible for data generation or validation, who provides feedback, and how results are communicated. In doing so, they align seamlessly with the principles of ISO 14040 and ISO 14044, which mandate clarity, consistency, and transparency in life-cycle studies.

7.4. Survey on application scenarios of the model

The analysis of the survey results reveals several important findings regarding the usability and applicability of the model, particularly in relation to different user groups. First, the general comprehensibility and clarity of the model were evaluated positively by both laymen and experts, indicating that the model effectively communicates its intended content. However, both groups found it challenging to assess the model's relevance and adaptability in practical scenarios, suggesting that while the model is theoretically sound, its practical application may require further refinement.

A notable observation is the difference in perspective between experts and laymen regarding the future use of the model. The experts generally did not express a strong inclination to reuse the model in their work. This could be attributed to their extensive experience with LCA, which may reduce their need for standardised process descriptions provided by the model. Experts likely have a deeper understanding of LCA processes and may not require a tool designed to guide them through basic or standardised procedures.

In contrast, feedback on the model's utility for beginners was more positive. This is evident from both expert feedback and the responses from laymen. Experts acknowledged the potential of the model as an introductory tool for LCA, particularly for those new to the field. This positive reception is further supported by the responses of laymen, where 12 of 16 participants rated the model 3 or higher on its usefulness. These findings suggest that the model may be more suitable for beginners and non-experts, serving as a valuable educational resource.

Another key finding is that nearly all experts' survey participants (3 of 4 rated 4, and 1 rated 3) agreed that the relevant aspects of LCA are well represented in the model. This outcome aligns with the primary goal of the study, which was to ensure that the model effectively covers the essential components of an LCA. Positive feedback in this regard suggests that the model fulfils its intended purpose, at least in terms of content coverage.

The high ratings given by experts for the model's compliance with ISO 14040/44 standards underscore its robustness and adherence to internationally recognised guidelines for LCA. This alignment with ISO standards is crucial, as it ensures that the model is not only theoretically sound but also practically applicable within the frameworks commonly used in industry and research. However, the isolated score of 0 in this area suggests that there may be specific elements of the model that require further refinement to fully meet the stringent criteria set by these standards. The expert who provided the negative score offered detailed feedback on the aspects that needed improvement to meet ISO compliance, and these suggestions were subsequently adapted to the model. However, this highlights the importance of continuous validation and iterative improvement of the model to address any gaps and ensure that it remains compliant with ISO guidelines in all aspects.

Interestingly, the survey revealed that laypeople demonstrated greater proficiency in PASS modelling compared to their familiarity with LCA, which can be attributed to the educational context in which the survey was conducted. Many of the lay participants were students who had previously attended courses at the institute where they were introduced to PASS modelling as part of their curriculum.

When analysing the feedback on the SID and SBD separately, distinct patterns emerge. The SBD received criticism for being overly detailed, particularly for novices, as it requires a foundational knowledge of the LCA terminology. This may present a barrier to entry for beginners, indicating that the model could benefit from simplification in this area. In contrast, the SID was consistently praised for its effectiveness in demonstrating the interactions between various actors within an LCA process. This suggests that while the model may need adjustments to cater to different levels of expertise, its conceptual approach to illustrating LCA interactions is well-received.

Furthermore, the results of the survey underscore the general importance of LCA, as recognised by both experts and laymen. This is particularly true in the context of decision making for the development of new products, where both groups rated the importance of LCA highly. This trend reflects a positive shift towards the incorporation of environmental assessments into product design, highlighting the growing awareness of sustainability in decision-making processes.

In conclusion, the model shows promise as an educational tool, particularly for beginners in LCA. However, its practical relevance and adaptability to expert users appear limited, which could be attributed to the advanced knowledge that experts already possess. The strong emphasis on the importance of LCA in both environmental assessment and decision-making is a positive trend that supports the continued development of tools like this model. Further refinements, especially in simplifying complex diagrams and enhancing adaptability, could make the model more universally applicable across varying levels of expertise.

7.5. Limitations of the used methodology

First, the deductive analysis employed in this study relied on a pre-established theoretical framework derived from existing literature on LCA processes. Although this approach provides a structured mechanism for extrapolation, it inherently assumes that the initial theories and norms are stable and comprehensive. However, if LCA norms and frameworks are adapted or updated in the future, as they have been in the past, the derived framework in this study may not capture these new developments. This limitation could result in the model becoming outdated or misaligned with the latest standards, thereby reducing its validity and applicability in future LCA practices.

Second, while the application of expert interviews is effective in aggregating expert opinions, it may have inadvertently promoted a convergence toward consensus that overlooks outlier perspectives. In this study, the potential for groupthink could result in a model that reflects a median view rather than capturing the full spectrum of expert insights, particularly those that might challenge conventional approaches. This could limit the model's robustness and adaptability, particularly in scenarios where unconventional or emerging practices in LCA are relevant. Additionally, the relatively small and potentially homogeneous group of experts involved can introduce bias that affects the generalizability of the model across different LCA contexts.

Third, surveys, by their design, enable the capture of a broad spectrum of perspectives, ranging from laypeople to experts. While this range ensures a diversified data set, the depth and granularity of acquired knowledge could be compromised. Laypeople lacking domain-specific knowledge might inadvertently introduce noise into the dataset. Furthermore, survey methodologies are susceptible to several biases, such as response and sampling biases.

Furthermore, within the context of the survey, defining and measuring 'expertise' remains challenging. Experts with different experiential backgrounds can offer contrasting or even conflicting insights, which complicates the validation of findings.

8. Summary and outlook

In conclusion, providing a correct understanding of LCA processes for involved humans is one of the main goals of this research, and it is necessary for the long-term resilience of – in our case – establishing/accepting LCA processes and their results as useful and necessary part of advancing towards Industry 5.0. Although the presented model takes a holistic approach, it may not capture all the nuances that some stakeholders consider essential. However, it is not the primary aim of the model to provide an exhaustive description of every detail with utmost precision, as this level of granularity is typically addressed by relevant ISO standards. It should rather act as an introductory guide for beginners to the subject of LCAs, offering a straightforward overview and rapid insight into the complexity of the topic.

Building upon the initial verification conducted through a survey, it would be necessary to incorporate more comprehensive studies to assess the benefits of using the proposed model in the LCA process. Specifically, these studies should focus on evaluating how different stakeholders involved in the LCA process, such as LCA analysts, company representatives, data managers, and external reviewers, interact with and can benefit from the model. The goal is to gain a deeper understanding of how the model supports these individuals in fulfilling their roles within the LCA framework. In addition, studies should explore how the model improves the ability to navigate the complexities of the LCA process, improve communication among stakeholders, and whether the model can contribute to more accurate and efficient assessments. This expanded research would help determine the model's effectiveness in real-world applications beyond the initial survey and provide insights into potential areas for further refinement.

Therefore, more comprehensive studies could be done to assess the benefits of using the proposed model to introduce newcomers to the topic of LCA. Since the SBD was described as somewhat overwhelming, smaller versions could be created for this purpose with fewer scientific terms or more explanations. As well as fewer scientific terms, the model could be particularly beneficial when used in conjunction with an example, as many newcomers are often introduced to the subject through examples. Using the model, it would be possible to provide a clearer understanding of each individual's role and the current stage in the process.

In order to evaluate the impact of the proposed model within higher education, we intend to conduct a comparative study involving students who are required to perform an LCA study each semester. The aim of this research is to explore how the introduction of the model alters the students' approach to conducting the LCA study and whether the process can be expedited compared to a control group that has not been introduced to the model.

After evaluating the contributions of various stakeholders during the LCA process, such as LCA analysts, company representatives, data managers, and external reviewers, future research should focus on exploring potential adjustments to the proposed subject-oriented model to better address the unique needs and concerns of these individuals. These needs may include improving the clarity and usability of the model, improving communication and coordination among stakeholders, and ensuring that the model remains adaptable to different contexts and evolving LCA practices. To achieve this, future research could involve designing and conducting targeted experiments or case studies that simulate real-world LCA scenarios in combination with the proposed model. These studies would provide deeper insights into how the model can be refined to more effectively support stakeholders in performing LCAs.

Subsequent studies could focus on more detailed modelling of specific aspects, particularly critical processes such as cascading, crediting, impact assessment, and the comparability of different LCA studies. The continued refinement and expansion of the model, including the inclusion of more specific and detailed aspects, is expected to lead to a better understanding of the environmental impacts of products and processes. To further elucidate the proposed models, especially for beginners in the field, a case study could be presented with reference to the models. This would provide a practical illustration of the theory, enhancing comprehension and promoting effective application in real-world scenarios. This could lead to LCA studies that provide even more accurate results and serve as a solid basis for decision-making on environmental concerns. Furthermore, the model is expected to be further extended and refined in the future to meet the changing needs of the evolving environmental and legal landscape, adding value to businesses and decision makers.

At a minimum, the human-centric analysis of the LCA process provides valuable insights by means of visualisation and description of the LCA process with a focus on human involvement, thereby establishing the groundwork for a human-centric LCA approach that can be implemented in the future.

Author contributions

Conceptualization, L.G.; writing – original draft preparation, L.G. and S.H.; writing – review and editing, L.G., S.H. and M.E.; visualisation, S.H. and M.E.; supervision, J.O.; All authors have read and agreed to the published version of the manuscript.

Declaration of Generative AI Usage

During the preparation of this work, the authors used ChatGPT and Writeful AI-based language models to improve language and readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. The authors declare no financial or non-financial competing interests that could have influenced the research outcomes.

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Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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