Sustainability in Product Models: Leveraging Adjacent Information for CO_2 Profiling in Configurations

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Abstract: This paper introduces the concept of Sustainability Adjacency as a framework for integrating adjacent information into CO_2 profiling and product configuration systems. By leveraging supplementary data, such as supplier emissions, logistics, and lifecycle assessments, the framework enables a comprehensive evaluation of a product's sustainability impact. Current sustainability initiatives often operate in silos, neglecting broader trade-offs like transportation emissions in refurbishment or end-of-life scenarios. The proposed framework addresses these gaps by centralizing critical data, ensuring its propagation across organizational functions to prioritize low-emission configurations. Through an action research approach, the study highlights systemic barriers, including data quality issues, supplier transparency, and misaligned workflows, that hinder CO_2 profiling efforts. The findings emphasize the importance of dynamic data integration and cross-functional collaboration in aligning sustainability with operational and financial goals. This paper contributes to advancing sustainable product models and outlines actionable steps for organizations to embed sustainability into product lifecycle management effectively.

1 INTRODUCTION

The growing importance of sustainability requires organizations to define, design, control and operationalize systems to maximize the value of product offerings over the complete product life cycles (Krikke, 2011; Brundage et al., 2018; Di Biccari et al., 2018). This is further intensified by the European Commission through the introduction of new proposals addressing critical aspects of climate change and environmental degradation, with the aim of achieving a climate-neutral continent by 2050 (Campo Gay et al., 2024). According to (McKinsey & Company, 2020), there is a correlation between the assessment of product components and carbon emission profiles, whereas organizations have set explicit emission-reduction goals. Moreover, the robustness of information, data and system capabilities determines the computed CO_2 profile, helping organizations meeting greenhouse-gas (GHG) regulatory targets and reporting requirements (Hallstedt, 2017; Chauvy et al., 2019; He et al., 2019; Jakobsen et al., 2024a).

Despite these advancements, accurately profiling CO_2 emissions across complex product configurations remains a significant challenge for many organizations (Jakobsen et al., 2024a). This complexity arises from the need to integrate diverse data sources and adjacent information to generate reliable and actionable insights (Chauvy et al., 2019).

Impactful CO_2 profiling requires robust information systems and knowledge management that account for variability in materials, production processes, and supply chain dynamics (Shafiee et al., 2018; Campo Gay et al., 2024; Jakobsen et al., 2024a). Leveraging adjacent information, such as lifecycle assessments, material flow data, and energy consumption metrics, can enhance the accuracy of these profiles (Krikke, 2011; Badurdeen et al., 2018; Brundage et al., 2018; Kalita et al., 2021). As organizations strive to meet greenhouse-gas (GHG) reduction targets and align with regulatory demands, developing scalable systems for dynamic CO_2

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profiling has become a critical priority (McKinsey & Company, 2024). These systems not only improve compliance but also enable strategic decision-making to enhance sustainability across product lifecycles (Badurdeen et al., 2018; Di Biccari et al., 2018).

This complexity highlights the importance of leveraging advanced digital tools like life cycle assessment (LCA) configurators, which enable organizations to integrate sustainability considerations early in the product development phase. Dynamic assessment of environmental impacts, including CO_2 profiling, is facilitated by automating processes and integrating real-time data (Campo Gay et al., 2024). Leveraging adjacent information, such as lifecycle data, material properties, and energy consumption metrics to improve accuracy and comprehensiveness for the sustainability element of the product model. The potential of this is demonstrated by Zubair et al. (2024) as integrating LCA with digital tools in building construction could lower CO_2 equivalent emissions by roughly 29% during the raw material phase, 16% in the operational phase, and 21% at the end-of-life stage when compared to traditional practices. Such advancements highlight the role of data-driven methodologies in aligning product configurations with sustainability objectives, ultimately promoting informed choices that balance technical performance and environmental impact (Campo Gay et al., 2024; Jakobsen et al., 2024a).

Product modelling is a representation of structured product information and data in respect to material selection, design choices, and part ranges, which impact the sustainability outcomes of product models (Lee et al., 2007; Badurdeen et al., 2018). Leveraging adjacent information, sustainability becomes a system property and not a property of individual elements of systems (Ceschin & Gaziulusoy, 2016). This perspective emphasizes that sustainability become apparent from the interactions and interdependencies within the system relatively than from isolated components (Ceschin & Gaziulusoy, 2016). In product modelling, adjacent information e.g., supply chain data, LCA, energy use patterns, and end-of-life disposal options, enables a holistic evaluation of a product's sustainability impact (Campo Gay et al., 2024; Jakobsen et al., 2024a). This systems-level approach ensures that material selection, design configurations, and part choices align with sustainability objectives, accounting for trade-offs and synergies across the entire lifecycle.

Therefore, the purpose of this paper is to explore the role of adjacent information in advancing sustainable design practices through enhanced product modelling in a computing environment. Specifically, it aims to identify the types of adjacent information required for optimizing solutions in documenting environmental labels and declarations, such as lifecycle data, material properties, and supply chain metrics. By examining how such data interconnects within product modelling frameworks, this study seeks to demonstrate how adjacent information facilitates the development of data-driven methodologies for sustainability. Additionally, this paper seeks to demonstrate the integration of these elements into a computing system enhances the sufficiency and accuracy of sustainable design practices.

2 THEORETICAL BACKGROUND

2.1 Sustainability in Product Lifecycle Management

Quantifying the environmental performance of products and conducting comprehensive environmental evaluations are guided by the principles outlined in ISO 14040 and further elaborated through the detailed methodological framework provided in ISO 14044 (Campo Gay et al., 2024). However, sustainability information is not easily shared between stages in the product lifecycle as there is a gap in manufacturing through data and knowledge sharing (Brundage et al., 2018). This is intensified in industry as more data is being generated at exceptional rates and variation than ever before (Komoto et al., 2020). Product Lifecycle Management (PLM) involves the synchronisation of product design, manufacturing workflows, software platform interoperability, and the continuous synchronization of data across various enterprise applications (Jakobsen et al., 2024b). Literature connects PLM and sustainability into sustainable product lifecycles and designs considering the three important aspects, i.e., economics, social, and environmental (Kalita et al., 2021). In other words, maximizing the product lifecycle profit, and minimizing energy and water usage over the complete lifetime (Kalita et al., 2021). Jakobsen et al. (2024b) highlight that the relationship between PLM and sustainability remains ambiguous, emphasizing the need for a comprehensive assessment of data interoperability to support sustainable practices and optimize product lifecycle management within digital systems. Additionally, sustainable practices in PLM must address critical decisions on material selection, design methodologies, and product end-of-life processes, including recycling, reuse, and disassembly (Vila et al., 2015). These phases, described as the foundation of Green PLM, require integrating eco-design principles, advanced manufacturing processes, and efficient waste management strategies to minimize environmental impacts for sustainability (Vila et al., 2015). In other words, knowledge, information, and data for PLM in respect to sustainability is used for the materials and processes selection based on product modelling criteria needed in the design of product parts (Vila et al., 2015).

2.2 CO_2 Profiling and Environmental Impact Assessment

The assessment of sustainability in products has become an area of increasing focus among both academic researchers and industry professionals. The development of CO_2 profiles for product models is constrained by defined system boundaries, as illustrated in figure 1. These profiles and their impact assessments are primarily centred on Global Warming Potential (GWP), a key component of Life Cycle Assessment (LCA) analysis (Brunø et al., 2013; Briem et al., 2019; Campo Gay et al., 2022). Consequently, the evaluation of CO_2 profiles for product models relies on analysing the environmental impacts of a product system within the framework of an LCA (Brunø et al., 2013; Briem et al., 2019; Campo Gay et al., 2022)

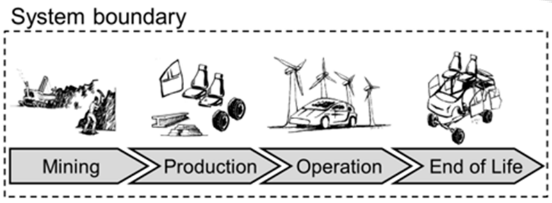

Figure 1: System boundary, adopted from (Briem et. al 2019).

The attributional LCA methodology is structured around a defined framework and specific objectives. From a PLM perspective, attributional LCA traditionally adopts a static and retrospective approach to evaluating the product lifecycle (Briem et al., 2019). However, the development of CO_2 profiles and the assessment of environmental impacts in product modelling depend on informed decision-making, driven by the availability of environmental data and sustainable options (Campo Gay et al., 2022; Campo Gay et al., 2024). Additionally, Campo Gay et al. (2022) emphasize that the construction of a CO_2 profile relies on available options and product specifications. To reduce the CO_2 equivalent, it is essential to prioritize sustainable choices and integrate these into the customer's decision-making process. This can be achieved, for example, using a computing configurator that facilitates sustainability considerations and guides customers toward more environmentally friendly options (Shafiee et al., 2018; Campo Gay et al., 2024; Jakobsen et al., 2024a). Furthermore, effective CO_2 profiling depends not only on product-specific data but also on adjacent information, such as supply chain emissions, material sourcing, and manufacturing processes (Helo et al., 2024). Integrating this broader spectrum of data ensures a more accurate and holistic representation of a product's environmental impact, thereby enhancing the customer's ability to make informed and sustainable choices.

2.3 Adjacent Information in Product Models

The concept of adjacent information in product models refers to the supplementary data and contextual knowledge that exist outside the core technical specifications of a product but remain critically relevant to its analysis and decision-making processes (Bates, 1989; Nonaka & Takeuchi, 1995). This supplementary information includes elements such as supply chain logistics, environmental impacts, material sourcing, manufacturing practices, and end-of-life considerations. Integrating adjacent information into product models allows for a more comprehensive evaluation, bridging the gap between isolated product data and the broader lifecycle impacts (Bates, 1989; Nonaka & Takeuchi, 1995). For example, while a product model might detail the material composition and structural design, adjacent information can provide insights into the CO_2 emissions associated with raw material extraction, transportation, or production methods.

This integration emphasizes the compilation of multiple information systems, such as enterprise resource planning (ERP), manufacturing execution systems (MES), and LCA tools, to enhance product documentation and decision-making (Badurdeen et al., 2018; Komoto et al., 2020; Jakobsen et al., 2024a). These systems contribute product insights into dynamic and interconnected factors, such as environmental compliance, cost analysis, and production scalability. By consolidating adjacent information into product models, organizations can move beyond static documentation and adopt a holistic, context-aware approach.

The contextual relevance of adjacent information lies in its ability to inform decisions that extend beyond the technical engineering design paradigm, such as aligning production goals with sustainability metrics or optimizing resource allocation to reduce waste (Krikke, 2011; Shafiee et al., 2018). In simpler terms, adjacent information helps connect the dots between the technical details of a product model and the broader objectives of an organization, such as reducing the environmental impact. This can be translated into supporting the structure of selecting eco-friendly materials, improving logistics to minimize emissions, or designing products that are easier to recycle at the end of their life (Shafiee et al., 2018; Campo Gay et al., 2022; Campo Gay et al., 2024).

2.4 Computing Environments for Sustainable Design

The computation of LCA knowledge in a product modelling environment is a complex task, and it is not well understood how this knowledge can be automatically implemented into systems (Campo Gay et al., 2024). According to Campo Gay et al. (2022) literature is very limited within this area and suggest applying the Product Variant Master technique (PVM) to assess the knowledge from domain experts in an ontology model. The principles of modelling mechanical products and systems theory are applied to define the structure within the PVM (Mortensen et al., 2010). This structures the configuration system's structure and its computing environment, aligning it with the product families to be modelled, and the user requirements for the configuration system (Mortensen et al., 2010). Figure. 2. Demonstrates the principles of PVM. A product variant master comprises two main components. The first component, known as the "part-of" model (represented on the left-hand side of the product variant master), includes the modules or parts common to the entire product family (Mortensen et al., 2010). Each module or part is further detailed with attributes that define their properties and characteristics.

The second component (illustrated on the right-hand side) outlines how a product part can exist across multiple variants. These two structural types, "part-of" and "kind-of," correspond to the aggregation and specialization structures found in object-oriented modelling (Mortensen et al., 2010). Similar to the "part-of" model, the individual parts here are also characterized by attributes. Additionally, the product variant master specifies the critical relationships between modules or parts, including the rules governing their permitted combinations (Mortensen et al., 2010). This is visually represented by connecting lines between modules or parts, accompanied by the relevant combination rules.

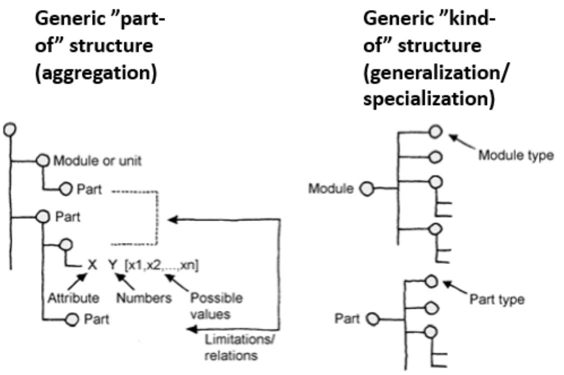

Figure 2: Principles of the Product Variant Master, adopted from (Mortensen et al., 2010).

The PVM technique serves as a tool for data collection and communication, organizing product knowledge to facilitate discussions about the product model (Campo Gay et al., 2022). This is illustrated below in figure 3.

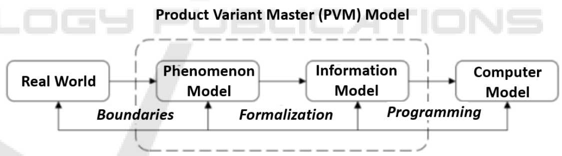

Figure 3: Conversion of knowledge from the real world to the computing model, adopted from (Shafiee et al., 2019).

The computing environment for product modelling for sustainable designs requires product knowledge within the defined solution space (possible configurations) (Shafiee et al., 2019). The computation of product modelling tools is employed for documenting and facilitating communication in product configurations (Shafiee et al., 2019). The product modelling manages the increasing complexities of software development, allowing engineers to operate and communicate at more abstract levels while ensuring comprehensive documentation within its computing environment (Shafiee et al., 2019). In addition, Shafiee et al. (2019) emphasize the PVM technique to enhance knowledge sharing across organizational units, which contributes considerably to an organization's performance. Having an impactful system for the sustainability aspect of documenting the structure, attributes, and constraints modelled within the computing environment is essential, as well as ensuring communication between developers and domain experts (Badurdeen et al., 2018; Shafiee et al., 2019; Komoto et al., 2020; Jakobsen et al., 2024a).

The complexity of knowledge sharing and communication of product models remains a challenging task. The integration and complexity of adjacent information, such as supply chain data, environmental impacts, and operational constraints into product models remains underexplored. This gap is significant as adjacent information can enhance decision-making by enabling a more holistic view of the product lifecycle within sustainable design context. The novelty of adjacent information into computing environments supports the alignment of sustainable practices with organizational goals, linking abstract product knowledge and real-world applications. Addressing this gap is crucial for advancing computing environments that can manage the complexities of sustainability-driven product design and configuration processes.

3 RESEARCH METHOD

This paper aims to contribute to the literature on sustainability in product models by leveraging adjacent information for CO_2 profiles in configurations. The overall objective is to develop a framework of adjacency for sustainable configuration processes. This involves collecting examples and cases of adjacent information relevant to configuration management for sustainability in product models. To provide a foundation for the proposed framework an action research methodology was chosen as it facilitates experimentation aimed at improving conditions within an existing organization, enables the application of methods in real-world settings (Gummesson, 2000) and simultaneously contributing to literature (Shani & Pasmore, 1982).

The action research methodology for this study is conducted in an industrial manufacturing company, specializing in energy-efficient fluid management and pumping technologies. This collaboration is done to meet the stated research objectives to generate and collect knowledge in the current solution space of adjacency for product modelling. The concept of adjacency aligns closely with knowledge management principles, addressing challenges in situations where existing organizational systems and resources are insufficient to solve emergent system-level problems (Shafiee et al., 2018).

In the context of this action research study, adjacency is an extension of knowledge management (Shafiee et al., 2018). The approach was designed as an iterative and participatory process involving the creation, storage, transfer, and application of knowledge, actively engaging stakeholders to enhance the knowledge business value chain and address practical challenges within the organizational setting. This approach includes the identification and collection of adjacent information in product models across the complete business value chain and throughout the entire lifecycle of adjacency knowledge. The assessment involves mapping systems, data, information, and knowledge to align with sustainability goals in product models for CO_2 profiling (Shafiee et al., 2018).

Data was collected through a combination of qualitative and participatory methods. This included conducting interviews and workshops with key stakeholders, reviewing internal documents and reports, and observing existing practices within the organization. The collected data focused on identifying instances of adjacent information relevant to configuration management and sustainability in product models. These activities ensured the inclusion of real-world insights and examples, which form the empirical foundation for developing the proposed framework of adjacency for sustainable configuration processes.

3.1 Case Company

The case company analysed in this study is a global leader in advanced fluid management and energy-efficient pumping technologies, headquartered in Denmark. Despite its strong market position and extensive experience in producing high-quality solutions across various industries, the company faces significant challenges in addressing the growing complexity of sustainability in product models. Currently, the most advanced form of sustainability documentation available for its product models is Environmental Product Declarations (EPDs) based on LCA data.

The organization operates within a distributed knowledge network where critical information on sustainability is scattered across various departments. However, existing systems and workflows do not adequately support the resolution of systemic issues related to sustainable product modelling. This gap results in reliance on manual and internal problem-solving efforts to meet documentation requirements for product models, often through ad-hoc processes and emergent knowledge-sharing practices.

As a consequence, the company struggles to establish cohesive and efficient methods for integrating sustainability into its product configuration processes. The knowledge required to address these challenges evolves dynamically within the organization, characterized by a high degree of improvisation and the gradual development of routines to manage the demands of sustainable product modelling. This study explores how these challenges can be addressed by leveraging adjacent information to create a more structured and impactful approach to sustainability in product models.

4 FINDINGS

Table 1 showcase a schematic representation of sustainability adjacency within the case company. The table provides a structured understanding of sustainability elements in relation to adjacent information flows across various corporate functions. It highlights the ways in which these functions contribute or fail to contribute to CO_2 profiling within product models. Furthermore, the evolvement of sustainability interpretations and representations over time has led to the establishment of several dedicated corporate functions in this domain, some of which are also embedded at the divisional level. These functions, ranging from Corporate Social Responsibility (CSR) to LCA, and Environmental, Social, and Governance (ESG) initiatives, offer unique perspectives and data islands that either directly or indirectly inform the company's sustainability practices. The table thus serves as a foundation for understanding the fragmented yet evolving landscape of sustainability in the organization.

This schematic outline reveals a diverse set of sustainability elements, each attached within distinct corporate functions. For example, while CSR primarily focuses on supplier assessments and social inclusivity, its role in CO_2 profiling remains indirect, offering contextual support rather than direct integration into product models. Similarly, the Retrofit function emphasizes economic sustainability through market opportunities for extending product life cycles, yet it lacks measurable contributions to CO_2 profiling. In contrast, functions like ESG and LCA emerge as pivotal contributors. ESG facilitates alignment with sustainability legislation and integrates raw material and production data into reporting frameworks, thereby supporting CO_2 profiling efforts. LCA, on the other hand, provides the most robust connection, directly addressing life cycle impacts and forming a core data source for CO_2 profiling within product configurations.

The findings also underscore significant gaps in integration, particularly in functions such as Quality and Financial. While these functions are crucial for compliance and governance, their contributions to sustainability often remain isolated from broader CO_2-focused initiatives. This fragmentation is further compounded by the existence of "data islands," which slow unified information sharing and systemic alignment. Such challenges highlight the need for a more cohesive framework that bridges adjacent information across corporate functions to enhance the organization's capacity for sustainability-driven innovation.

The findings also reveal that customers are primarily driven by sustainability factors such as water and electricity savings, with a growing emphasis on the CO_2 profile of product models. However, a critical gap exists within the case company, as its adjacent information systems and workflows do not sufficiently align with the customers' focus on CO_2 profiling. Current sustainability documentation relies on Environmental Product Declarations (EPDs), which are generated through LCA data. These processes are heavily dependent on manual data handling, such as the use of Excel spreadsheets and tacit knowledge sharing. This reliance on fragmented and labour-intensive methods prevents the seamless integration of adjacent information into product models, thereby limiting the company's ability to meet customer expectations for transparent and comprehensive CO_2 profiling. Addressing this misalignment will be essential for bridging the gap between customer demands and the company's internal capabilities, ensuring that sustainability initiatives are both impactful and scalable.

4.1 Mapping Sustainability Adjacency in Product Life Cycle Models

To address the critical gaps identified in the case company's sustainability practices, it is essential to map sustainability adjacency across the product life cycle. By structuring the analysis around distinct phases of the product life cycle: (1) Mining, (2) Production, (3) Operation, and (4) End of Life, the table 2 highlights not only the system information storage supporting each phase but also the associated data gaps and challenges. This approach offers a comprehensive funnel through which to evaluate the

Table 1: Schematic representation of sustainability adjacency.

	Function	**Data islands**	**Integrated data**	**Sustainability Focus**	**CO_2 Profiling in Product Models**
CSR	Broad assurance for responsible behaviour. Supplier assessment. Specific ruleset control, e.g. modern slavery act, conflict minerals, child labour, dual-use products, general human rights, labour rights, supply chain inclusivity, water stewardship	Reports on each separate issue	Supplier assessments	Social and environmental aspects	Indirectly relevant: Supplier data can inform the social and environmental dimensions of product models
Retro-fit	In the case company, a separate entity has been tasked with creating a business area of product retrofitting. There is no evidence of greenhouse gas reduction by doing so. However, it is important to present the opportunity to the market	Operating proce-dures	Product data catalogue Product data manage-ment Warehou-sing	Economic sustainabili-ty by extending product life cycles and exploring retrofitting	Not relevant: The focus is on exploring market opportunities for retrofitting
Social econo-mic action	For many years, the case company have operated an inclusive workshop for impaired persons. The workshop receives products from worldwide and do various disassembling and circularity tasks	Perfor-mance reports. Circular impact	None	Social sustaina-bility	Limited relevance: highlights circular economy practices
ESG	The ESG function is specifically tasked with data collection and reporting in formalized frameworks of sustainability management. Typically, alignment with national and EU legislation in the field	ESG reporting	Certain production figures are used. E.g. to present data on use of raw materials and subassemblies	Holistic sustaina-bility covering environ-mental, social, and governance dimensions	Relevant: ESG data includes integrating raw material use and production characteristics into product models, CO_2 profiling
LCA	Looking at specific products for design-time, (configure-time), production-time, in-use, and end-of-life issues. This can relate to specific materials, assemblies, residuals, and behaviours	Spread-sheet for representati on	None	Environmenta l sustaina-bility through the evaluation of lifecycle impacts and material usage	Highly relevant: LCA addresses the environ-mental impacts of product mo-dels across their lifecycle: data for CO_2 pro-filing product configurations
Quality	The quality function would look at product compliance and – in some cases – production optimization. The focus is originally customer satisfaction, but this seems to play a smaller role. Quality is related to both suppliers, and internal processes. Increasingly the compliance element is non- related to either, but rather related to regulatory and legislative requirements	Quality reports	Quality approvals and documents on parts and subassemblies. Some work instructions	Regulatory compliance and process optimization for sustaina-bility	Partially relevant: Quality assurance contributes to compliance but offers limited CO_2 -specific data
Finan-cial	Financially related sustainability governance issues. Include internal and arms-length controls, sustainable taxation, anti-corruption, anti-money laundering, KYC, independence of key profiles, and financial resilience	Financial and non-financial audits are document-ted as islands	Financial data Transactional approvals Credit approvals	Governance-related sustaina-bility, focusing on ethical and financial practices.	Not relevant: Primarily focused on governance and financial accountability

Table 2: Mapping Sustainability Adjacency in Product Life Cycle Models.

Life Cycle Phase	**Description**	**System Information Storage**	**Data Gaps & Challenges**
Mining	Extraction of raw materials (e.g., metals, minerals) needed for production.	ERP, LCA Tools	Limited supplier transparency, incomplete environmental data on sourcing, and difficulty integrating with LCA tools.
Produc-tion	Manufacturing and assembly of components and products.	PLM, MES, ERP	Fragmented data between systems, lack of real-time environmental monitoring, and insufficient integration with CO_2 models.
Opera-tions	Use phase, including energy consumption and performance monitoring.	IoT Platforms, ERP, CRM	Inconsistent data from IoT devices, lack of standardized metrics for CO_2 profiling during operation.
End-of-life	Disposal, recycling, or repurposing of the product after its operational life.	ERP, LCA Tools, Sustainability Plat-forms	Inadequate tracking of recycled materials, limited data on actual end-of-life scenarios, and manual processing of environmental data.

interplay between corporate functions, data systems, and the organization's ability to meet customer demands for CO_2 profiling.

The mining phase, while ERP and LCA tools play a role in tracking raw material sourcing and environmental data, significant barriers such as limited supplier transparency and fragmented data hinder the integration of sustainability insights. Similarly, during the production phase, the reliance on PLM, MES, and ERP systems is accompanied by challenges such as the lack of real-time environmental monitoring and insufficient CO_2 model integration. These gaps continue to later phases, such as the operation and end-of-life stages, where inconsistent IoT data, inadequate tracking of recycled materials, and manual data processing remain obstacles to achieving seamless sustainability alignment.

The quality of data has been identified as the most critical factor for achieving traceability within the product life cycle. Supplier transparency and fragmented data, already evident at the initial phase of the life cycle, the mining phase operate as significant barrier. At this stage, raw material suppliers often report and document LCA data of questionable quality, likely due to inconsistencies in data collection, lack of standardized reporting frameworks, or limited oversight. This lack of reliable data flows throughout the supply chain, affecting subsequent phases such as production and operation. The poor data foundation established during mining impacts not only the accuracy of downstream processes but also the integrity of outputs like EPDs, which are critical for communicating sustainability credentials to customers. Furthermore, these limitations hinder the ability to produce strict and transparent CO_2 profiling for product models, undermining internal capabilities of trust in the product documentation in respect to sustainability documentation.

The quality of data is not only a critical factor for traceability but also a foundation for achieving effective configuration management of product models and accurate CO_2 profiling. At its core, high-quality data serves as the foundation for creating reliable product configurations that reflect environmental impacts across the life cycle. When supplier transparency and fragmented data are compromised, the ripple effects saturate throughout the supply chain, leading to inaccuracies in material and process data. This, in turn, undermines the ability to build accurate and detailed life cycle inventories, which are essential for configuring sustainable product models. Given this context of product configuration management, poor data quality impedes the integration of sustainability attributes into product configurators. For example, if the LCA data originating from raw material suppliers is incomplete or inconsistent, it becomes challenging to model the environmental impact of materials and components in a way that aligns with customer expectations for CO_2 transparency.

Emphasizing data quality within the broader context of sustainability adjacency contributes to a more intense understanding of the systemic barriers to CO_2 profiling. These findings expand the horizon by uncovering critical misalignments in the documentation and reporting processes of product models' life cycles, offering actionable insights into areas that require strategic improvement. Improving sustainability adjacency within the case company means advancing stronger connections between multiple systems and aligning sustainability elements with adjacent information flows. By bridging gaps between systems in respect to sustainability data, configuration management, and life cycle reporting, the case company positions itself to respond proactively to regulatory requirements and market expectations.

4.2 Structuring Computation of Sustainability Data

The ability to compute sustainability data successfully centres on the structured organization adjacent information in product models across product life cycle phases. Each phase: (1) Mining, (2) Production, (3) Operation, and (4) End of Life, represents a distinct perspective or "view" within the broader system boundaries of sustainability assessment. The figure 4 illustrates how sustainability data can be modularly structured, connecting attributes, limitations, and relations specific to each phase. By employing this modular approach, the case company can better capture the intricate interdependencies between raw material sourcing, production processes, operational energy consumption, and end-of-life disposal or recycling. This structure not only supports LCA but also enables a cohesive integration of sustainability data into product configuration processes, forming the foundation for accurate CO_2 profiling and EPDs.

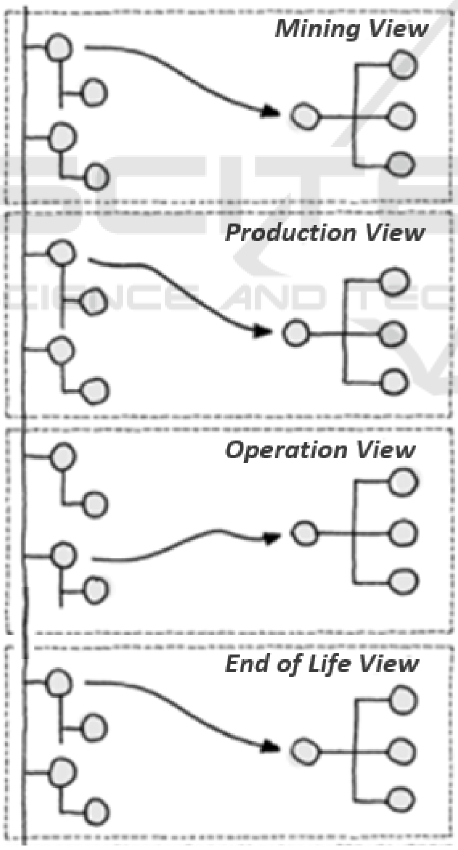

Figure 4: Modular data structure with connected attributes and relations.

The practical application of structuring sustainability data is exemplified in the computational integration of life cycle data for the THETA series pumps. Utilizing EPD data, this approach aligns life cycle stages: (1) Production (A1-A3), (2) Transportation (A4), (3) Assembly (A5), (4) Use (B6), and (5) End of Life (C1-C4), with adjacent systems such as ERP and PLM to create a modular framework for CO_2 profiling. This method highlights the critical role of LCA data quality in configuration management.

Each life cycle phase is treated as a distinct module containing specific attributes and relations. For example, the Production phase includes raw material data (e.g., percentages of cast iron, copper, and plastics) and energy consumption metrics, while the Use phase incorporates operational electricity usage (e.g., 46.88 kWh/year for Gr1 pumps). Similarly, the End of Life phase captures recycling potentials (e.g., 1.62 kg of recyclable cast iron) and waste fractions. These modules are computationally linked to adjacent systems to streamline data integration. ERP systems provide sourcing data for raw materials and transportation emissions (e.g., 0.0322 Liters of fuel/100km for a 500km transport distance), while PLM systems link product variants to their respective material configurations and life cycle impact data. IoT platforms contribute real-time energy consumption metrics, enabling continuous monitoring of operational impacts.

The modular LCA structure allows for dynamic CO_2 profiling by aggregating data across life cycle phases. The total CO_2 profile for a pump configuration can be calculated by summing input material emissions (e.g., 12.5 kg CO_2 eq. for A1-A3), energy use during operation (e.g., 14.5 kg CO_2 eq. for B6 over 10 years), and recycling benefits at the end of life (e.g., -1.33 kg CO_2 eq. from Module D). This modular approach also facilitates scenario modelling, enabling comparisons between configurations with varying material compositions or energy efficiencies. Integrating this computational framework into configuration management tools further enhances its utility. Embedding modular LCA data into the product configurator allows customers to select product options (e.g., high-recycled-content materials) and view real-time CO_2 impact estimates. "Kind-of" relations within the configuration process enable categorization into sustainability-focused variants, such as Standard vs. Eco-variant THETA pumps. Furthermore, sustainability dashboards visualize life cycle emissions for each configured product, broken down by module (e.g., A1-A3, B6), providing transparency and actionable insights for customers.

This structured approach not only improves data traceability but also enhances the organization's ability to align with customer expectations and regulatory demands. By integrating modular sustainability data into adjacent systems, the case company achieves greater sustainability adjacency, bridging critical gaps in its documentation and reporting processes. This ensures that CO_2 profiling and EPDs are accurate, configuration-specific, and aligned with strategic objectives. Ultimately, this method supports the case company's broader goals of advancing sustainability integration across its product models and life cycle stages, while fostering innovation in sustainable product development.

4.3 Computing Automated Co_2 Profiling

The findings from the case study on the THETA-series pumps highlight the transformative potential of automating CO_2 profiling in the case company's product configuration processes. Following the computation concept of Campo Gay et al. (2024) the quantification of environmental metrics should be established using the appropriate environmental unit. This proposal follows the EPD standard as it includes a list of environmental units associated with a particular Product Category Rules (Campo Gay et al., 2022). According to the EPD standard, the selected environmental impact indicator unit was kg CO_2 eq.

The automation of CO_2 profiling relies heavily on the seamless integration of multiple data sources and systems, with the product configurator serving as the central platform to interconnect these systems. This integration allows for real-time computation of product model emissions across all relevant life cycle phases. By aggregating data from disparate systems, the configurator ensures that emissions are calculated dynamically and with precision, offering significant improvements in efficiency and transparency compared to traditional manual approaches. The product configurator orchestrates the flow of data between critical systems, including PLM systems, ERP systems, IoT platforms, and EPD/LCA databases. Each of these systems contributes and provides essential data to the profiling process. PLM systems provide material composition and manufacturing data, such as the percentage of cast iron, copper, and plastics used in production. ERP systems supply logistical information, including transport distances and fuel consumption, which are necessary for calculating transportation emissions. IoT platforms monitor real-time operational data, such as energy consumption during the use phase, ensuring high-resolution and up-to-date metrics. Lastly, EPD/LCA databases deliver recycling rates and end-of-life impact factors, enabling the accurate assessment of emissions and benefits during the product disposal phase.

The integration of these systems into the product configurator ensures that data is aggregated and processed in real time. For example, in the case of the THETA-series pumps, material composition data retrieved from the PLM system indicates that the product consists of 60% cast iron, 30% copper, and 10% plastics, resulting in a production-phase impact of 12.5 kg CO_2 eq. Transportation data from the ERP system reveals that a transport distance of 500 km, with fuel consumption of 0.0322 liters per km, contributes 0.32 kg CO_2 eq. IoT-enabled monitoring of operational energy consumption over the pump's 10-year lifetime adds 14.5 kg CO_2 eq., while end-of-life recycling data from the EPD database offsets emissions by -1.33 kg CO_2 eq., reflecting the recycling of 1.62 kg of cast iron. These values are aggregated to compute a total CO_2 profile of 26.67 kg CO_2 eq. for the product configuration as demonstrated in figure 5.

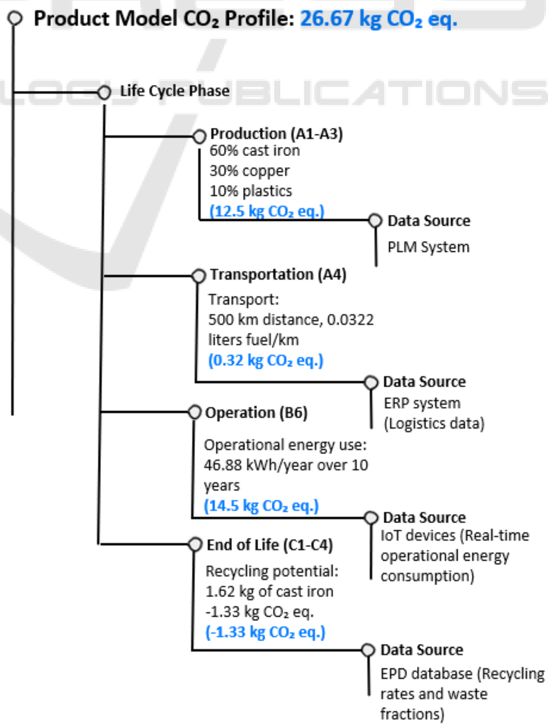

Figure 5: CO2 profile break-down structure.

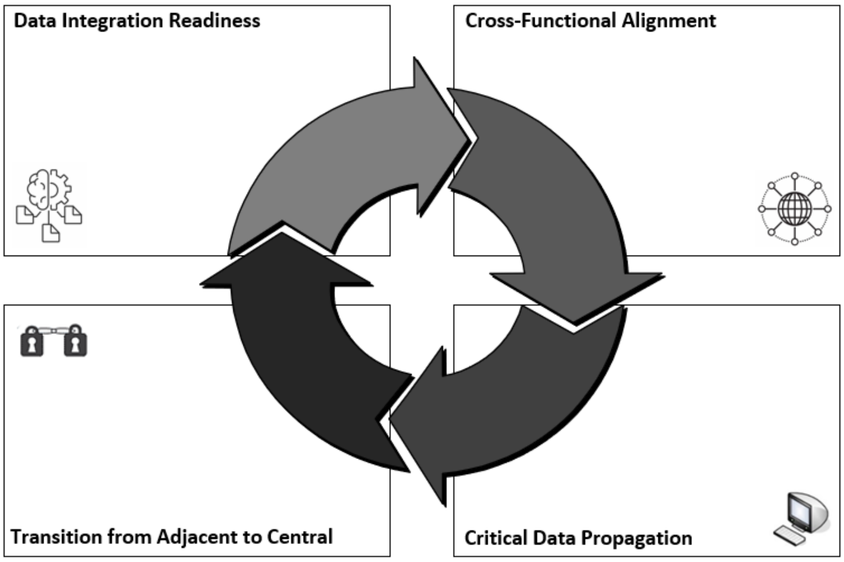

Figure 6: Sustainability Adjacency Measurement Model.

The product configurator facilitates not only real-time computation of emissions but also scenario modelling and customer interaction. By dynamically updating the CO_2 profile based on configuration choices, the configurator enables customers and engineers to simulate the impact of various design options, such as selecting recycled materials or optimizing energy efficiency. Choosing recycled steel in the production phase reduces emissions by 30%, offering customers clear insights into the sustainability benefits of their decisions. This interconnected system architecture is critical for leveraging the computation of CO_2 profiles for each configured product models. By adopting this automated CO_2 profiling breakdown structure, the case company not only improves the efficiency and accuracy of its sustainability assessments but also strengthens its ability to align with regulatory requirements and meet evolving customer expectations. Moreover, the integration of multiple data sources into a unified platform positions the case company in sustainable environment of product configuration, leveraging advanced computational tools to drive environmental responsibility.

4.4 Sustainability Adjacency Measurement Model

To address the integration of adjacent information and enhance sustainability in product models, this paper proposes the Sustainability Adjacency Measurement Model. The proposed model was developed in close collaboration with the case company. The primary focus was on addressing a key organizational challenge: consolidating LCA data from suppliers into a unified platform. This model provides a structured framework to evaluate an organization's maturity in leveraging adjacent data for sustainability-driven product design and configuration processes. The model is designed to ensure that critical sustainability data transitions seamlessly from isolated systems to centralized decision-making processes.

The proposed model (figure 6), represents key components of the framework, starting from foundational data integration readiness and culminating in the transition from adjacent to centralized decision-making for sustainability. Arrows indicate the flow and interdependence between the key components, highlighting the progression towards actionable insights.

The **Data Integration Readiness** evaluates the organization's ability to integrate "island" data sources into a centralized system. These data sources include isolated repositories, legacy systems, and departmental datasets that are often inaccessible or incompatible with centralized platforms. Integration readiness involves both technical and organizational readiness.

The **Cross-Functional Alignment** assesses collaboration between departments (e.g., CSR, finance, operations) to ensure consistent sustainability strategies. Cross-functional alignment emphasizes the coordination of efforts to ensure sustainability data and insights are shared, understood, and acted upon across all relevant functions. The relevance of this alignment seeks to break down organizational silos to achieve holistic sustainability outcomes. In other words, ensuring critical data is accepted, interpreted consistently, and utilized across functions. This is essential and critical to avoid conflicting strategies, e.g., approving an environmentally friendly supplier in CSR while finance disapproves due to cost concerns.

Critical Data Propagation measures the extent to which critical data from specialist departments (e.g., PLM) influences organizational decision-making. This component evaluates whether data relevant to sustainability, such as CO_2 profiles, supplier compliance, or material assessments, is effectively transmitted and utilized at higher organizational levels. This facilitates the integration of domains in relation to specialist knowledge, ensuring critical sustainability metrics are prioritized. Impactful propagation of such data bridges the gap between departmental silos and sustainability-related actions.

The **Transition from Adjacent to Central** evaluates how effectively adjacent sustainability data transitions into actionable insights for product design and operations. Adjacent data refers to supplementary information such as supplier environmental performance, lifecycle assessments, and operational efficiency metrics, which are critical but not originally centralized. The transition enables organizations to transform fragmented or supplementary data into strategic inputs that directly impact product development, supply chain decisions, and sustainability reporting. For example, incorporating adjacent supplier data (e.g., CO_2 emissions from logistics) into centralized product design decisions.

4.5 Distributed Sustainability Data Adjacency for Systems

The Sustainability Adjacency Measurement Model aligns seamlessly with the developed UML diagram (figure 7) by emphasizing the systematic integration of sustainability data across distributed information systems. The quadrant-based approach highlights critical enablers such as Data Integration Readiness, Cross-Functional Alignment, Critical Data Propagation, and the Transition from Adjacent to Central, which are foundational elements reflected in the UML's structured interconnections between key entities like ProductModel, DataSource, and EnterpriseInformation. For example, the UML notation emphasis on data accuracy and reliability metrics directly supports the Data Integration Readiness quadrant by ensuring that sustainability data from multiple sources can be seamlessly incorporated into centralized configurations. Similarly, the propagation of CO2EmissionData across various lifecycle phases mirrors the Critical Data Propagation quadrant, enabling real-time decision-making and alignment with sustainability objectives. Together, these models provide a robust mechanism to operationalize sustainability within complex systems, bridging the gap between adjacent information sources and centralized decision frameworks.

From a computational perspective, the Sustainability Adjacency Measurement Model leverages modular data structures and relational mappings, as demonstrated in the UML notation, to address systemic barriers in sustainability data management. The model’s Data Integration Readiness component is operationalized through entities like DataSource and EnterpriseInformation, which utilize attributes such as ProcessBoundary, DataAccuracyScore, and EnergyMix to assess and validate the completeness and accuracy of incoming sustainability data. These attributes enable seamless integration of heterogeneous data streams into centralized systems, such as ConfigurationEngine, which employs rule-based optimization algorithms to align product configurations with sustainability thresholds.

Critical Data Propagation is implemented via directed relationships between CO2EmissionData and downstream entities like LifecyclePhase and LCA Metrics. This propagation ensures that sustainability metrics such as GlobalWarmingPotential and EutrophicationPotential are dynamically computed and passed through the system to inform both operational decisions and long-term strategic planning. By leveraging these interconnections, the UML notation translates adjacent data into actionable insights, enhancing the scalability and robustness of sustainability-driven computational workflows. Furthermore, the framework's ability to accommodate distributed architectures allows for concurrent processing and integration across multi-tiered systems, ensuring consistency and reliability in sustainability calculations.

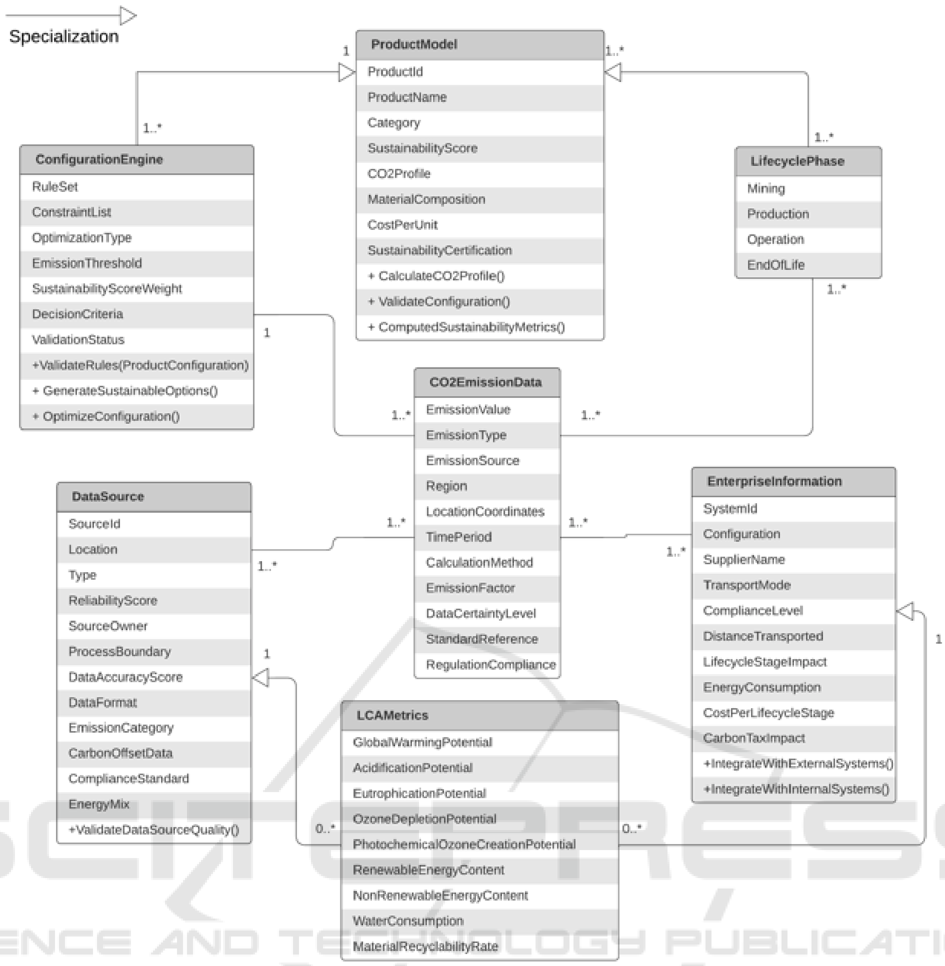

Figure 7: UML Representation. Sustainability Adjency Measurement Model.

5 DISCUSSION & CONCLUSION

A critical aspect of this paper lies in the concept of sustainability adjacency, which emphasizes the need for continuous integration of supplementary, yet crucial, data sources into centralized sustainability decision-making processes. But also realising that most data in the field exist isolated and out of reach in more holistic decision-making processes. Embedding CO_2 profiling into product configuration systems leverages adjacent information, such as supplier emissions data, logistics, and end-of-life scenarios, to create a more comprehensive lifecycle assessment. This approach addresses critical gaps in current sustainability initiatives, such as the underestimation of transportation emissions in refurbishment or take-back programs, which often neglect the broader environmental trade-offs. By integrating adjacent data into real-time decision-making, organizations can prioritize low-emission options throughout a product's lifecycle, ensuring sustainability objectives are not siloed but actively influence every stage of design and configuration. This shift not only enhances transparency and operational efficiency but also equips businesses to meet evolving regulatory requirements and customer expectations in a sustainability-driven market.

The sustainability adjacency framework aims to highlight organizational areas requiring greater attention, particularly where current sustainability initiatives operate as isolated efforts rather than being dynamically aligned with data flows or processes such as product development activities. The framework seeks to capture and map critical data, ensuring its propagation to a central level where CO_2 product profiles become integral to decision-making. By embedding this data into the product configuration process, the framework ensures that low-emission configurations are consistently prioritized. This also establishes shared organizational constraints and interdependencies across departments, fostering streamlined collaboration. For instance, a rule within the framework could ensure that a product component chosen for its low carbon footprint is simultaneously cost-effective and compliant with procurement policies, balancing environmental, financial, and operational goals.

However, the impact of CO_2 profiling face several systemic barriers, including data quality issues, supplier transparency, and misaligned workflows. These challenges hinder the seamless adoption of sustainability initiatives and reduce the accuracy and reliability of CO_2 assessments. Data quality issues and/or inconsistent or incomplete data from internal and external sources is a major barrier to effective CO_2 profiling. Lifecycle data often originates from disparate systems, including supplier databases, operational records, and environmental reports, which may not align in format, granularity, or reliability. Poor data quality compromises the accuracy of CO_2 profiles, leading to suboptimal decision-making. Addressing this requires implementing robust data governance practices, such as standardization of data formats, validation protocols, and real-time data integration.

A significant portion of a product's CO_2 emissions appears from supply chain activities. However, suppliers lack the systems or willingness to provide detailed environmental data. This complexity creates gaps in the lifecycle assessment, limiting the ability to generate accurate CO_2 profiles. Encouraging supplier transparency through collaborative frameworks, standardized reporting requirements, and sustainable practices can mitigate this issue, fostering better alignment between suppliers and manufacturers. Organizational silos and disconnected processes can prevent sustainability data from being integrated into decision-making. Procurement teams may focus on cost efficiency without access to environmental data, while product developers might prioritize design functionality over sustainability. Misaligned workflows result in fragmented efforts that fail to capitalize on sustainability opportunities. Addressing this requires restructuring workflows to embed sustainability data and objectives into core operations, ensuring collaboration and alignment across all departments.

The adoption of the sustainability adjacency framework carries significant implications for industries heavily reliant on complex supply chains and internal business units. As consumer demand for sustainable products continues to intensify, businesses face increasing pressure to allocate resources toward adopting and integrating CO_2 profiling into product models. However, this effort often conflicts with maintaining both internal consistency and external credibility, as the complexity of creating, managing, and aligning sustainability data across multiple systems remains largely uncharted. Without robust strategies to address these challenges, organizations risk fragmenting their sustainability efforts, undermining their ability to deliver measurable environmental impact.

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