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Research article

Parametric life-cycle assessment for configurable products in high-mix manufacturing

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ABSTRACT

High-mix manufacturers face challenges in delivering product-specific environmental data at required time. Traditional life cycle assessment (LCA) is a post-hoc tool that requires intensive manual work in calculating product-variant impact. This study proposes a solution by developing and evaluating a parametric LCA that can generate product-specific environmental assessments when production orders are completed. Using a design science approach, the proposed solution is tested in pipe manufacturing which produces many product variants. The study methodologically contributes to modelling multi-process parametric LCA for various products using the product geometry and routing running time as main parameters. Moreover, the study also positions parametric LCA as a core methodology for product service system transition in which automated environmental data is considered as a service when bundled with physical products in high-mix manufacturing supply chains. The paper focuses on addressing the challenges of managing a wide variety of products and generating self-declared life-cycle analysis reports for each product variant. This solution is designed to develop the product configuration process using up-to-date software solutions that support order-handling processes in case-by-case situations for companies, while maintaining environmental sustainability.

1. Introduction

Businesses exert environmental pressure through resource extraction, production processes, and waste management, prompting policy makers to require them to disclose their environmental impacts. To address this need, companies require new digital tools to manage their sustainability practices and demonstrate transparency and accountability in their operations, which necessitates access to up-to-date, reliable data (Haanaes and Olynec, 2022). From explicit data, such as material characteristics, product architecture, process design, and configuration, to implicit data, e.g., supply chain resources and consumer preferences, manufacturing data can be recorded at every stage of a product's existence. This requirement extends the traditional manufacturing and supply chain for a physical product to a product-bundle product-service system (PSS). The primary enablers of achieving data-driven production are the collection and analysis of manufacturing data.

In addition to manufacturing data, environmental data is required for many physical products. The incorporation of environmental considerations into product development and design can help businesses address environmental issues and meet customer demands by minimizing negative environmental impacts throughout a product's lifespan (Bianco et al., 2021). From one perspective, it suggests a methodical approach to product knowledge, assisting those responsible for environmental issues in gathering environmental data and converting it into helpful design recommendations. The other offers a method for efficiently using this information in the early stages of the product design process. Organizations discard environmental studies (such as life cycle assessments and product ecological footprints) with poorly organized data that are neither internally acknowledged nor capitalized; they are given numerous sustainability criteria but are unable to prioritize them (Bianco et al., 2021).

Managing sustainability, such as quantifying the environmental impacts of one's business, can be challenging due to the complex supply chain and manufacturing process. Each product may require multiple raw materials sourced from different regions and transported by various modes, which are then processed through various manufacturing processes. Furthermore, the data is dynamic, continuously changing to

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reflect actual sourcing, transportation, and manufacturing. The dynamic nature of supply chains adds another layer of complexity to managing sustainability (Seuring and Müller, 2008; Haanaes and Olynec, 2022). Managing sustainability also requires expertise in life cycle assessment (LCA) to gather and process data into meaningful, communicable information for stakeholders. Often, companies do not manufacture a single product; instead, they offer products that differ but share similar characteristics or even functions (a product family). Under the environmental product declaration (EPD), each product should have a separate LCA, though if the results differ by more than 10%, they may be combined in a single report (Seuring and Müller, 2008). Continuously calculating each product separately requires significant resources.

Parametric LCA could be a substitute for traditional LCA in handling high data complexity and uncertainties (Arias et al., 2025). Implementing parametric LCA in high-mix manufacturing addresses the gap between static, post-design environmental assessment versus dynamic, real-time eco-design in customized product systems. It could allow automated environmental calculation by translating manufacturing process parameters into mathematical functions. At the theoretical level, concerns regarding inventory analysis in LCA and the granularity of environmental disclosure remain unaddressed (Arias et al., 2025). Traditional LCA assumes a static inventory in which the structure does not change with the product. It is sufficient for mass-produced products but falls short for configurable products, where routings depend on design decisions that vary across orders. Moreover, the calculation for mass products cannot achieve configuration-level granularity. Prior studies have not addressed inventory structures that change following configuration adjustments, nor have they applied parametric LCA to product variants that undergo multiple routings. Hence, this study aims to handle sustainability data and assessments across a wide range of products within a supply chain using parametric LCA. The aim can be achieved by answering the following research questions (RQs).

- RQ1: How can parametric LCA enable product-bundle PSS in high-mixed manufacturing products and supply chains?
- RQ2: What data is necessary in parametric LCA implementation to handle product-level environmental disclosure in configurable manufacturing?

RQs are addressed by developing artifacts using a design science approach. The research will produce layers of contribution that primarily tap into advances in LCA methodology, focusing on how parametric LCA should be structured in configurable manufacturing contexts. The study will not advance digital service innovation (DSI); however, parametric LCA in high-mix manufacturing structurally depends on digital infrastructure. The BOM and BOO that provide the interaction between configuration and inventory are structures that exist within the enterprise system as part of the digital layer. DSI facilitates operational data to be repurposed into environmental information using parametric LCA logic. It is therefore an enabler for artifact realization. By conducting the study, we also demonstrate how product-service bundling can be achieved through parametric inventory construction to generate configuration-level environmental data.

The rest of the paper is organized as follows: Section 2 outlines a literature review of product family management and product platforms and defines the configuration process. Section 3 presents the study methodology, focusing on life cycle assessment within the context of a product configurator. Section 4 presents the study results with respect to the case company's product, calibration model, four tested components and the associated software. The study concludes in Section 5, along with its contribution.

2. Literature review

Digital service innovation has been characterized by the emergence of new outcomes, distributed governance, and co-design, but processes are often built on combinatorial evolution (Vargo et al., 2024). Earlier studies have shown that the need for digital service innovations for sustainable development has been addressed across all three areas of environmental, social, and economic sustainability (Heinz et al., 2025). The idea of using product information modelling for product life-cycle management itself is not new. Frameworks for efficient operations have been presented in the field of computer-aided design, e.g., Sudarsan et al. (2005). Life-cycle information models have been linked to LCA in decision-making (Bhat et al., 2021). However, there is novelty in applying digital service innovation to provide an efficient operational solution for linking design, manufacturing, and life-cycle phases in a generic-purpose operational solution. What remains unexplored is how to integrate operational solutions to connect LCA and product-family-level configurations to provide real-time sustainability services in high-mix production. Therefore, we review prior work on sustainability-related data management for product development, product-service systems, product platforms, and product configurators as operational tools for solving the problem, and synthesize their limitations.

2.1. Data management for sustainability in product development processes

Many businesses have begun including sustainability data to assess their performance and product development procedures. It will help them ensure uniformity and comprehensiveness in the practice of measuring sustainability. Sustainable data and analysis in businesses can support sustainable development in evaluating the long-term sustainability of products and services (R. Rabetino et al., 2024a,b). To incorporate sustainability concerns into the design and development of a new product, design management—the field that provides tools and techniques to support managers and technicians throughout the design process—plays a crucial role. In this case, assessment during the design phase proved to be crucial because it undoubtedly makes it simpler for manufacturers to reduce their impact on the environment, adhere to safety regulations, and simultaneously satisfy consumer demands and financial constraints when the primary features of the product are still unknown (Lucky et al., 2019).

A fundamental idea in environmentally friendly production and utilization for both business and policy, life cycle thinking (LCT) aims to consider every link in the supply chain when assessing the sustainable development of product systems (Strazza et al., 2016). LCA is a widely accepted approach for integrated environmental assessment of goods and services (ISO, 2006a; ISO, 2006b). In accordance with ISO 14025 (ISO, 2006c), type III environmental labeling, or Environmental Product Declarations (EPDs), is now recognized as a means of disseminating reliable data on a product's environmental impact derived from an LCA analysis (Del Borghi, 2012). EPDs serve the needs for traceability of origin, environmental impacts, and other global logistics chain-related requests.

Over the coming decades, methods for assessing a product's sustainability will continue to advance quickly. Managers can create a procedure that best meets their company's requirements by understanding the fundamentals of sustainability performance tracking (Fargnoli et al., 2014). Managing manufacturing and sustainability data can be a useful tool for complying with the European Union's impending digital product passport regulations (Wicaksono et al., 2025). To provide customers, suppliers, and government agencies with information about the social and environmental impacts of their products—such as resource consumption, carbon footprint, and labor conditions—an effort will establish a product lifecycle archive. Examples of applying product passport data to life-cycle data have been presented for plastic recycling (Tabata and Tsai, 2025) and the automotive industry (Popowicz et al., 2025).

Data management streamlines compliance procedures, dismantles organizational silos, and provides insight into a product's carbon footprint throughout its lifecycle. A unified data management system for thorough insights is the first step towards creating sustainability programs that are more feasible and effective. The recent discussion of digital product passports and other data-governance requirements also requires a systematic way to ensure up-to-date versioning of processes and operational sites. These parameters are also key factors in selecting traceable emission factors. Most existing approaches focus on design-time sustainability data or on purely reporting-oriented approaches, without supporting product-variant-level high-mix production systems.

2.2. Data management for product service innovation system

The product service innovation system (PSIS) describes product-level innovations that have a positive environmental impact throughout the product's life cycle. It encompasses innovations in waste reuse, emission avoidance, energy conservation, resource reduction, and entering the eco-product market (Schiederig et al., 2012). The most extensively used PMIS is ISO 14001. PMIS is a management standard that helps businesses identify, quantify, and control their environmental impacts. An ISO 14001-certified company must adhere to the plan-do-check-act cycle, which entails defining a green strategy and the measures and plans that follow, carrying them out, monitoring their implementation, and taking remedial action when necessary.

Multiple stages of the PSIS lifecycle—design, production, distribution/logistics, usage, and end-of-life—impact the environment. Considering this, it is emphasized that a methodical PSIS development approach is necessary, focusing on two elements: the “value co-creation” and “data-driven” approaches (Machchhar et al., 2022; Naeem et al., 2024). The value co-creation approach is portrayed as a “win-win” for competing consumers, and the data-driven approach offers a move towards an “informed” development process (Gaiardelli et al., 2021). Understanding the numerous opportunities to gather data throughout the PSIS lifecycle and the ability to extract information based on its application phase are crucial for leveraging the potential of the acquired data.

Consumers are becoming more concerned about the environment due to global warming and resource depletion, which has led to a conversation about sustainable manufacturing and consumption practices (Papagiannakis et al., 2019). Meanwhile, companies are under greater pressure to produce and deliver value to customers. In the past, businesses have frequently used the product sales model, sometimes known as the “product model”, in which they manufacture goods and then sell the ownership of those goods to customers. The servitization business model has recently gained popularity as a green company strategy that can meet customer demands while using less energy and raw materials (Zhang et al., 2022).

The accessibility of data is acknowledged as a critical component for PSIS and deployment (Borangiu and Polese, 2017). By enhancing current services and creating new ones, it generates an additional source of value. But there is still a lack of general knowledge on how data and knowledge support value creation and servitization (Zhang et al., 2022; Zambetti et al., 2023). The power of data in the servitization area to create value for both producers and consumers has been acknowledged by numerous instances and studies (Baines and Lightfoot, 2013; Opresnik and Taisch, 2015; Lehrer et al., 2018). The advancement of data-enabled PSIS is currently hampered by a lack of knowledge regarding how to use data efficiently (Zhang et al., 2022; Opazo-Basáez et al., 2023; Naeem et al., 2024). These services have been referred to by several names, but for clarity, we shall call them data-driven product service systems (DDPSSs).

We can conclude that, despite growing recognition of product service systems built on data-driven approaches, tangible mechanisms to embed LCA into supply chains and production remain largely unknown.

2.3. Product platforms for sustainable product family management

Many businesses have expanded their product offerings to meet growing consumer demand. A high product mix can help manufacturers expand their market, but it can also result in higher costs and longer lead times for new variants. It creates trade-offs between meeting customers' needs and being cost-effective, which can be managed by leveraging platform-based product development and product family design (PFD) (Ceschin and Gaziulusoy, 2016; Andersen et al., 2023). A product platform is the collection of assets—parts, procedures, technologies, and expertise — that are distributed across several products a company sells. Goods created on that same platform are called variants, and a product family comprises all the variants.

Novel strategies have been put in place to address various problems associated with platform development and PFD. These methods' effectiveness has been evaluated through case studies and applicability to various industry sectors (Simpson et al., 2006; Helo et al., 2024). Some of the factors driving the adoption of innovative development methods are shorter product life cycles, rapidly evolving technology, heightened global competition, and customers' demand for a wide range of options (Wheelwright and Clark, 1992). Businesses across a wide range of industries are considering platform-based product development to address the complexity of offering a broader product range (Badurdeen et al., 2018). The sharing of parts, modules, and other resources throughout the product family is essential to this strategy, which orchestrates the construction of a range of goods utilizing the concept of 'platforms', or modules of components, in product family development. This platform enables simple production and significant savings in family design. Platform-based strategies are being considered by businesses across a wide range of industries to streamline operations and maximize returns on investments in marketing, production, and new product development.

Exploration on the relationship between sustainable design and product family architecture remains in its infancy, although both eco-design to improve sustainability and product family design with socio-economic efficacy have been thoroughly studied (Ceschin and Gaziulusoy, 2016; Kim and Moon, 2017). Presently, product family architecture should account for environmental performance to create an environmentally friendly product family (Psarommatis and May, 2024). Sustainable product family management strives to be economically viable and environmentally benign while also increasing societal benefits throughout their lifecycles (Camel et al., 2024).

Many product features, such as independence, adaptability, environmental sustainability, and level of complexity, can be considered when designing the product platform to shorten time-to-build and lower the running and purchasing costs of varieties based on the platform (Kim et al., 2016). The platform approaches used today recommend combining components in various configurations. According to Gedell et al. (2011), this is insufficient on its own to achieve greater development efficiency. Platforms must also support the development phases to reduce lead times and gain first-mover advantage (Wheelwright and Clark, 1992). Design engineers want information about the functionality each system and subsystem delivers, how these systems interact, their capabilities and limitations, and how they have been designed to support reuse in the early stages of concept development. It can be difficult to represent such data and may call for a range of modelling techniques and knowledge sources (Gaines and Shaw, 1992).

Sustainability at the product family level has been discussed in certain industries, but in the design domain, concrete operational mechanisms linking product features to environmental impacts are rarely established.

2.4. Product configurators as computer systems

Configurable products are one way to achieve widespread personalization. To create product specifications that satisfy customer needs, a customizable product is developed for repeated use throughout the sales-delivery phase (Christensen and Wiezorek, 2021; Zhang et al., 2024). Configurators are outstanding examples of computer systems that enable mass customization, since they facilitate the needs of product users and the generation and administration of configuration information. Configuration processes need to be combined across their data-modelling platforms to aid in the administration of product data, which is always evolving (He et al., 2021). A configuration management system can be built on top of a product data governance platform by adding configuration process data. The business can use the stored product data and configuration expertise to develop domain-independent modules that provide configuration services on top of the product data management system (Cannas et al., 2022; Kondrup Andersen et al., 2025).

Product configuration problems that can be solved using a constraint satisfaction problem (CSP) are frequently encountered in product design (Tan et al., 2017; Xu et al., 2020; Rossi et al., 2022). Additionally, constraint fulfilment modelling is useful for life-cycle cost and conceptual design (Fargnoli et al., 2014; Bianco et al., 2021). Nonetheless, sustainable development rarely uses constraint satisfaction modelling. The literature mostly discusses CSPs in the context of sustainable supply chain management (Lucky et al., 2019).

Product configurations are among the most effective applications of intelligent technology concepts. A subclass of software-based technical systems that focus on developing product specifications is called a product configurator. A product configurator can be identified as "a software-based expert system that supports the user in the creation of product specifications by restricting how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined" (Haug and Hvam, 2007; Badurdeen et al., 2018). Product configurations have produced several advantages for engineering-oriented organizations, including reduced delays, better product requirements, knowledge conservation, reduced resource usage for product requirements, customized products, reduced everyday tasks, greater shipment assurance, and reduced time for training and onboarding (Salvador and Forza, 2007; Hvam et al., 2008).

Numerous industries, including laptops, bikes, automobiles, aircraft, household items, healthcare equipment, custom-manufactured goods (such as steel), and manufacturing goods (such as valves, actuators, and controllers), employ product configurators. While many engineering-focused businesses use configurators effectively, they also face significant challenges. The product configuration literature has not been comprehensively synthesized, yet such an evaluation is important because it can consolidate recent research progress. A thorough analysis enables expert to understand configuration-related problems beyond their own domain. This broader understanding can help develop workable solution rather than isolated "islands of automation." It ultimately supports the effective creation, development, and deployment of product configurators (Helo, 2006; Zhang, 2014).

2.5. Parametric LCA, servitization, and configurator

Despite the emergence of configuration systems in industry, engineering solutions are typically not linked to parametric LCA or other sustainability data. Parametric LCA is defined as an LCA structure in which the inventory data is not fixed but depends on other values or mathematical formulas (Heijungs, 2020). Its application is driven by drawbacks in traditional LCA, which are static and lack adaptability, leading to slow feedback and limitations when applied to complex, high-variability systems (Garcia and Freire, 2017; Raut et al., 2025). Parametric LCA employs predefined variables, such as material type, geometry (thickness, diameter, length), running time, energy sources, etc., and mathematical formulas to rapidly calculate a large number of design combinations. Given its dynamic nature, adaptability and flexibility, parametric LCA appears to be a potential alternative to traditional LCA.

Existing studies on the application of parametric LCA are clustering around building, energy, and manufacturing sectors. Hollberg and Ruth (2016) proposed a solution to architectural design by simplifying and parametrizing the model. Other studies showed similarities in which parametric LCA was applied to optimize design and minimize impacts during the planning stage (Mowafy et al., 2023; Shadram et al., 2016; Soust-Verdaguer et al., 2017). The building sector generates complex data, including engineering design, material types, and recycled-material composition, for which parametric LCA could support decision-making. In the building sector, parametric LCA was primarily applied to a single building archetype by varying geometric parameters within a single configurable object, resulting in dimensional rather than combinatorial variation. In the manufacturing sector, the focus was on implementing parametric LCA for early-stage product development and ensuring transparent calculations. Some examples include a generic manufacturing approach with parametric energy modelling (Duflou et al., 2012) and parameter-based calculations in semiconductor manufacturing, which introduce criteria for eco-design (Huang et al., 2016). A parametric approach has also been proposed for specific evaluation questions, for example, additive manufacturing (Manco et al., 2023) and calculation transparency in battery manufacturing (Ma and Deng, 2022; Ali et al., 2025). These studies addressed process-level parameterization, but mainly within a single product or process rather than across a high-mix family. They focused on background data variability instead of foreground configuration-driven inventory. The products were seen as fixed, and the parameters applied to the process conditions, such as energy mix or machine efficiency, rather than the product configuration, so it was not possible to change the inventory structure through geometry changes. Some issues were also left unaddressed, such as the criteria for parametrization and the quantification of auxiliaries. Previous studies parameterized within a known product type, whereas this study focuses on a multi-process, product-specific routing across a high-mixed product range, where the inventory structure changes with configuration, and outlines a solution based on digital tools.

Servitization or PSS ranges from providing products to delivering results. Three main archetypes of PSS include product-oriented services (POS), use-oriented service (UOS), and result-oriented service (ROS) (Baines et al., 2007; Tukker, 2004; Tukker and Tischner, 2006). POS will allow clients to retain ownership of the product while bundling it with additional services (e.g., maintenance contracts or environmental information). UOS focuses on access and intensifies product use where the customers do not own the products and may use them exclusively, jointly, or simultaneously. Lastly, ROS requires customers to pay for guaranteed results, and the company retains ownership and responsibility for the infrastructure, operation, and maintenance. PSS is recognized to create environmental, societal, and economic value (Rabetino et al., 2024a,b). Nonetheless, not all PSS deliver sustainable solutions with the focus on sustainability has decreased during the evolution of PSS research, creating two branches: 1) PSS's environmental agenda, 2) PSS's design and development (Rabetino et al., 2018). This study sits at the intersection of these two streams, contributing to the environmental assessment methodology and PSS design practice enabled by digital infrastructure (Fig. 1).

DSI is an enabler providing structured BOM and BOO so that the connection between design parameters and inventories can be established. Parametric LCA is the logic that translates digital operation data into configuration-specific environmental impacts through parameter selection, boundary structure, and uncertainty analysis. Product-service bundling is the outcome of DSI and parametric LCA interactions. In this context, DSI becomes a structural prerequisite, as manufacturers need sufficient digital maturity to implement parametric LCA and achieve configuration-level outcomes. It was reported that businesses can foster environmental sustainability by harnessing digital technologies and their services (Bustinza et al., 2024). The study also showed that the conceptual framework demonstrates that companies with diverse

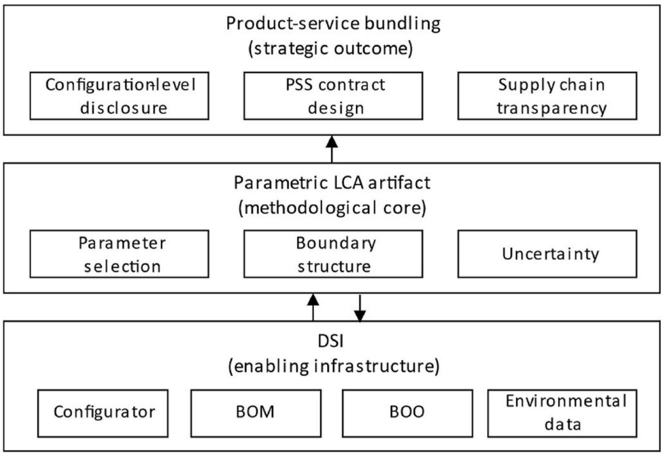

Fig. 1. Framework connecting PSS, artifact, and DSI.

innovations and optimized product lifespan are best positioned to harness the virtuous circle interconnecting digitization, sustainability, and competitiveness.

The reviewed literature shows progress across all areas of data management for sustainability, product service systems, product platforms, and configuration tools. LCA, as standardized reporting, seems predominantly unlinked to operational information systems. Earlier works on product-service systems focus on value creation rather than actual operational-level implementations, and product configuration systems do not link with sustainability data systems. This reveals the gap between the domains and motivates the opportunity to develop an artifact – the digital service solution by using a design science approach to demonstrate the solution.

3. Methodology

3.1. Design science approach

The study examines how companies can enhance competitive advantage while meeting sustainability requirements. The development of the solution follows a design science approach as outlined by Holmström et al. (2009) and Peffers et al. (2007). The design science approach was deemed suitable, as it can address a spectrum of problems and solutions involving multiple stakeholders, with outcomes that can provide answers for engineering applications (Tuunanen et al., 2024). The method covers five phases (Fig. 2) adapted and modified from Peffers et al. (2007): 1) problem definition, 2) objectives of a solution, 3) artifact development, 4) demonstration, and 5) evaluation.

The DRS application is designed to address the RQs. RQ 1 is addressed throughout phases 1-4. Phase 1 establishes how high-mixed manufacturing and product-bundle PSS create gaps in current LCA practice. It is followed by phase 2, which formulates the objectives to address the emerging research gap. In phase 3, the product-bundle PSS logic is integrated into the artifact by connecting design parameters to inventory modules. Phase 4 demonstrates how the artifact, working on high-mixed manufacturing, enables PSS-based contracts. Meanwhile, RQ 2 is explained in phases 3-5. The inventory data collection during phase 3 provides direct answers on what data are needed, but in phases 4-5 the claim is tested and evaluated.

3.1.1. Defining the problem and objectives of a solution

The first two phases include defining the problem and the objectives of a solution. The pressure from both regulatory bodies and customers to disclose the environmental impacts of products poses challenges and opportunities for businesses. It is a challenge to generate environmental reports for each product variant, whereas bundling the impact calculation as a service with the product can also increase competitive advantage. Some identified problems in producing environmental reporting include low interoperability between LCA software and other tools, data integrity issues, resource intensity, model simplification and methodology limitations. (Barbhuiya and Das, 2023; Haun et al., 2022; Olanrewaju et al., 2024). A conversation with local companies in the Ostrobothnia region that produce metal products also revealed that a lack of LCA knowledge among personnel and the high variety of products were the main challenges in moving toward sustainable operations. The main objective was then to develop artifacts that could transform the manual process of environmental impact calculation into a rapid, dynamic process capable of handling high-mix product variation. To be precise, the proposed solution.

- addresses sustainability requirements from regulatory bodies and customers,
- provides rapid calculation of each product family once the design parameters have changed,
- handles high product variety,
- it is easy to operate,
- it reduces manual workload in conducting the calculations.

3.1.2. Artifact development

The artifact should enable users to assess the impacts of high-mix products during the planning phase. Traditional LCA applies physical allocation by partitioning the input/output to the product being assessed. This approach is commonly implemented at the end of the financial year, when annual data is available, and will not allow companies to obtain results during the planning phase. Moreover, physical proportions may not accurately reflect the impacts of the production process, resulting in misleading outcomes (Sustainability Impact Metrics, 2025). The artifact should also make the application easier for users without extensive LCA knowledge, while simplifying the

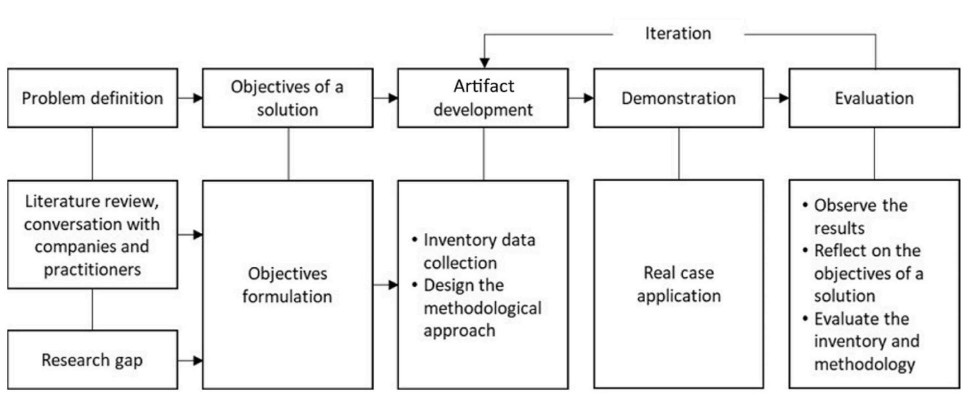

Fig. 2. Overview of the design science research (DSR) application in this study (adapted from Peffers et al., 2007)).

process and focusing on the most relevant aspects of the products. Therefore, the artifact development focuses on the cradle-to-gate stage, where companies have high-reliability data. The key to the proposed solution is a parametric LCA model in which the product-manufacturing processes are defined as parameters, enabling rapid adaptation across product families.

$$CC_v = CC_{alloc} + CC_{para} = CC_m + CC_t + CC_{rout} + CC_{aux} \quad (1)$$

The total impact of each product variant (CC_v) is the sum of impacts from materials (CC_m), transportation (CC_t), processing/routing (CC_{rout}), and auxiliaries (CC_{aux}). It can also be expressed as the result of the sum of impacts from traditional or allocation (CC_{alloc}) calculation and parametric method (CC_{para}) as illustrated in Equation (1) and Fig. 3.

The weight of the materials and the suppliers' locations are known to be used directly to calculate the impacts from materials and transportation, allowing ex-ante calculation. The gate-to-gate impacts traditionally performed post-hoc via physical allocation included impacts from processing/routing and auxiliaries' inputs. The processing is parameterized by the running time of manufacturing processes to rapidly calculate the impacts. Meanwhile, the auxiliaries' impacts are obtained by combining physical allocation and historical data. It will make the amount of auxiliary inputs known during the planning phase, since their association with product weight is based on historical data. The implementation of physical allocation for auxiliaries is deemed sufficient, as the associated impacts are generally insignificant. Moreover, there is even consensus that 5% threshold is the typical cut-off for impact contribution when practitioners choose to do so (Henriksen et al., 2019).

3.1.3. Demonstration

The proposed solution was applied to a local case company. The artifact is designed to address the need for a system that can reliably and rapidly calculate environmental impacts, given the high product variety. The case application is a Finnish company that produces industrial piping modules and subassemblies for high-risk environments, such as energy production, oil and gas, shipbuilding, and chemical processes. The company manufactures around 100,000 pipes and related components annually. These products include prefabricated pipes, individual pipe components, and complete pipeline systems manufactured from carbon steel and stainless steel.

3.1.4. Evaluation

The proposed solutions are evaluated for accuracy and robustness to

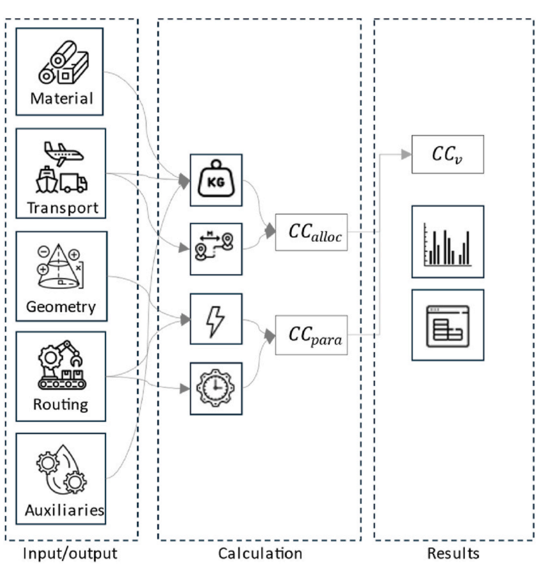

Fig. 3. Proposed solution workflow.

uncertainty. Accuracy refers to the differences in results between traditional LCA and parametric LCA. Traditional LCA here relies on allocation, in which the inventories and, subsequently, the impacts related to the product are proportionally distributed based on mass. Parametric LCA, in contrast, links impact directly to process routing and bypassing allocation. This means the two approaches are not strictly equivalent; hence, the accuracy comparison should be interpreted cautiously. This should be acknowledged as a structural limitation rather than a simple accuracy gap.

To assess uncertainty robustness, a Monte Carlo simulation was performed, along with key statistical indicators. A probabilistic sensitivity analysis was also conducted to identify which variables drive the assessment outcomes. Sensitivity analysis and Monte Carlo simulation were performed using Argo v4.1.3, an Excel add-in. A triangular distribution was used because the data are limited in terms of the full probability distribution. Companies generally do not track BOM and BOO data as full probability distributions. Company representatives could reasonably estimate the minimum and maximum beyond the most likely values. For the parametric LCA, the variability inputs stemmed from the power drawn during routing, which was later translated into variability in the model's output. The Monte Carlo simulation captures this propagation by sampling across possible input distributions. The inventory data was sourced from the case company and was not independently validated. It is quite a common limitation in industrial LCA studies where the organization supplies the data. It is noted that the results are valid as internal results and as a demonstration, rather than a verified environmental declaration.

This study offers a general methodological contribution, namely the parametric LCA framework itself, which links design parameters directly to the inventory through the routing-based function and hybrid structures that separate parametric-driven manufacturing from static weight-based upstream and auxiliaries. These are the principles proposed for other high-mix configurable products, where the design parameters govern the process runtime.

3.2. Demonstration of case application and proposed solution

The case application is the instantiation of the proposed artifact within a selected industrial context: pipe manufacturing. It is also a demonstration of how a company can shift from product selling to a product-oriented service (POS). Selling the pipes will still be the main objective; however, they are now being bundled with information about the impact of climate change. The choice aligns with the company's status, where customers still value ownership while addressing sustainability requirements. The company's customers use the pipe in high-risk environments that require permanent installation and cannot be shared/pooled as a use-oriented service (UOS). Furthermore, the challenge lies in data transparency for sustainability rather than physical products, so that bundling environmental information (as a service) with the pipes (the products) will add value without major restructuring of the business model.

The pipes come in different weights and dimensions, tailored to the customer's design, with weights ranging from 0.32 to 130 kg, diameters from 10 to 219 mm, and wall thicknesses from 1.73 to 12.7 mm. They were manufactured through welding, bending, cutting, drilling, and pressure testing. The impact boundaries were cradle-to-gate, meaning the study's scope included raw material extraction, material production, transportation, and pipe fabrication. The FU was a single pipe because the environmental performance information was associated with each manufactured pipe. By default, the impact will be characterized as self-declared environmental claims (Type II environmental labeling) under ISO 14021 (ISO, 2016). Four products (Fig. 4) manufactured in 2022 were used as examples in the study, reflecting differences in pipe size, weight, and the metalworking processes used during manufacturing.

The product configurator is used based on the customer's order, connecting design parameters and inventory. It serves as a tool to

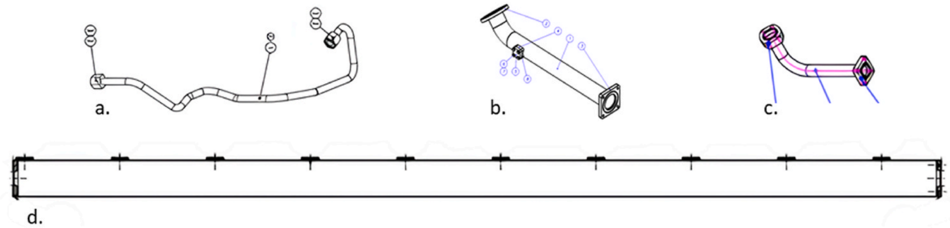

Fig. 4. Selected pipe for case application: a. Pipe 1, b. Pipe 2, c. Pipe 3, and d. Pipe 4.

streamline the design and manufacturing stages and support the rapid calculation of climate change impacts. Justification for using the process-minutes manufacturing driver instead of cell-level energy monitoring is that processing times can be stored in the configuration system's bill of material (BOM) or routing information. The same data can be used for manufacturing decisions and cost accounting. The planned consumptions and running time can be periodically verified against actual measurements to calibrate the timing used in parallel for production planning, timing, and emission calculations. Fig. 5 illustrates the product configuration, including the required inputs for calculating environmental impacts.

The data needed consists of foreground data (e.g., inputs and outputs) provided by the company, and background data for the associated emission factors (EFs) was obtained from Ecoinvent 3.11 (Ecoinvent, 2024) or local utilities for electricity. EFs refer to a value that quantifies the environmental impacts of a specific process or activity. The rapid calculation of process-based parameterization was demonstrated using Microsoft Excel for ease and clarity. The foreground data covers operational data from routing runtime and consumption of auxiliary materials, normalized per unit mass of the products. Parameter selection was based on whether the relationship between inventory quantity and product configuration could be expressed through a direct operation-level function. Parameters meeting these criteria correspond to the six routing operations: bending, cutting, welding, pressure testing, drilling, and compressor use. For each operation, energy consumption is directly linked to runtime, which in turn is associated with the pipe geometry or material type. Auxiliaries also vary with configuration, but the explicit routing function is too complex to parameterize at the operational level; therefore, it is modeled using output mass as an empirical proxy, with fixed consumption ratios derived from company records that express the weight of auxiliary material per kilogram of finished product.

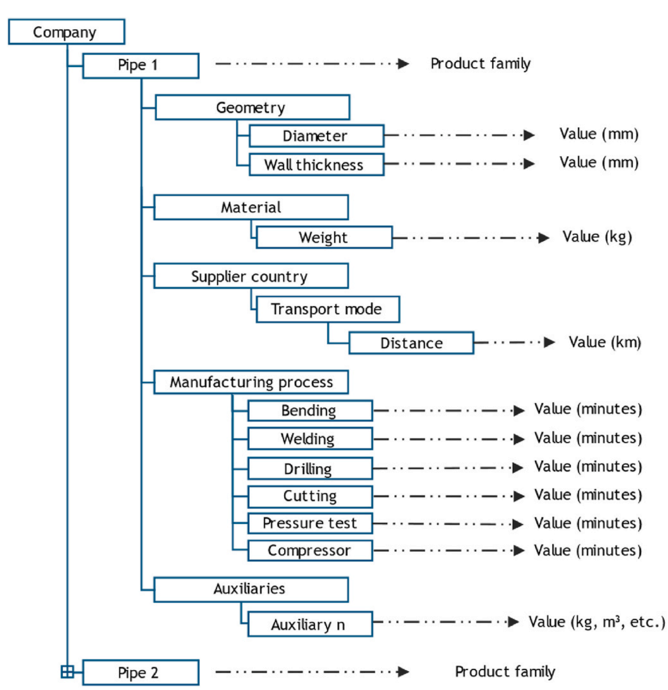

Fig. 5. Product configuration structure.

Fig. 6 summarizes how climate change impacts are calculated for each product family, with red boxes indicating the parametric LCA for rapid calculation. For the compressor, the running time was based on cutting, pressure testing, and drilling as those routings require a compressor. The company runs two compressors with different power, higher (compressor 1) and lower (compressor 2). The overall climate change impact of each pipe is the sum of impacts from material, transportation, auxiliaries, and the metalworking process/routings, calculated using the formulas shown in Equations (2)–(5).

$$\text{Material}: CC_m = Weight\ .\ EF_m \tag{2}$$

where CC_m refers to the impact of material production (e.g., carbon steel), *Weight* defines the material weight to produce a product family, and EF_m is the emission factor for the production of associated material.

$$\text{Transport}: CC_t = Weight\ .\ Distance_t\ .\ EF_t \tag{3}$$

where CC_t refers to the impact of transportation, *Weight* is the material weight in producing a product family, *Distance* shows how far the goods are being transported from one point to another point using a certain transportation mode, and EF_t refers to the emission factor associated with certain transport modes.

$$\text{Metalworking routings}: CC_{rout} = Power\ .time\ .\ EF_{el}\ .\ LF_v \tag{4}$$

where CC_{rout} is the impact of electricity consumption of certain manufacturing processes, *Power* is the electricity consumed by equipment as an average value observed by the company, *time* indicates the running time/length of a certain operation in minutes, EF_{el} refers to the emission factor associated with generating electricity, and LF_v indicates the load factor associated with pipe *v*. Equation (3) covers metalworking activities including drilling, cutting, bending, welding, pressure testing, and compressor. Load factors were employed in all metalworking except compressors. Electricity consumption during routing depends on pipe size; e.g., thicker-walled pipes consume more electricity than thinner ones. The load factor was calculated by dividing the wall thickness of the specific pipe by the thickest sample.

$$\text{Auxiliaries}: CC_{aux} = Weight\ .\ Input_n\ .\ EF_n \tag{5}$$

where CC_n is the impact from other resource consumption during the manufacturing process (e.g., water, lubricating oil, plastic packaging), including waste treatment if applicable. *Weight* refers to material weight used in products, $Input_n$ shows the amount of resource inputs per unit of weight (e.g., m^3 water per kg material weight), and EF_n is the emission factor associated with each input. Approximating $Input_n$ was conducted using historical data from their own manufacturing.

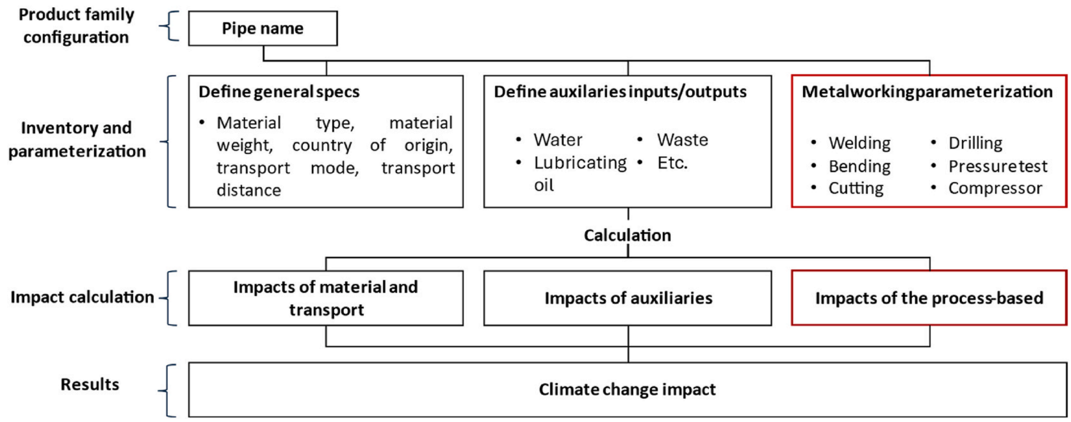

Fig. 6. Process sequence in product configuration to calculate climate change impact.

4. Results and discussions

4.1. Results of the design science approach application

The results are presented following the design science approach, which included artifact demonstration and evaluation results.

4.1.1. Artifact demonstration

The case example demonstrates the application of parametric LCA to prefabricated pipe manufacturing to enable rapid calculation of product variants and automate impact reporting. Nonetheless, the study's contributions are beyond parameter implementation and automated report generation. The study presents parameter selection logic for a high-mix product manufacturing context. The study defined the parameter selection criteria as governed by traceability and direct links between configuration and inventory at the operational level. It determines whether specific inventory belongs in the parametric layer or mass-allocation proxy. It connects to how the hybrid boundary structures combined a dynamic parametric model with a traditional static LCA. The hybrid boundaries were deliberate, showing that parametric implementation is justified when configuration-based variability is explicit and traceable, whilst applying parametric LCA across all boundaries may yield false outcomes. The logic of parameter selection and the justification of hybrid boundaries are independent contributions, not tied to the case application.

The configurator provides a reusable input data template to

Fig. 7. Comparison of the configuration of pipe 1 and pipe 4.

minimize manual labor when creating calculation models and stores mathematical formulas to reduce the number of manually entered data points (see Fig. 7). The inputs that required different information in each pipe included geometry, weight, and fabrication time for compressor use, as well as bending, welding, drilling, cutting, and pressure testing. The transportation distance and mode were the same because the suppliers were the same. Meanwhile, the auxiliaries were calculated by multiplying the weight allocation by the EFs.

Parametric LCA offers a dynamic, flexible LCA implementation by incorporating parameters and mathematical formulas, enabling instantaneous assessment that can be applied in the design stage. It enables the company to adopt product-related service models by bundling the impact calculation documentation with the products sold (see Fig. 8). The work also reported the automatic generation of results and the ability to handle product variants. The model can automatically update sustainability reports as inputs are adjusted, enabling decision support on the early production stage. The results were supported by a study that highlighted the importance of parametric LCA for assessing systems characterized by high variability (Arias et al., 2025). The proposed solution also allows users to dynamically test scenarios by varying parameters such as electricity sources or pipe characteristics (e.g., wall thickness or weight), or to couple it with other tools or methods, such as optimization, sensitivity or uncertainty analysis.

Various types of parametric LCA are increasingly used. Rule-based parametric LCA is a form of parametric LCA that follows a set of rules. The parameters are predefined based on guidelines, industry standards, or a set of requirements (Li et al., 2026). The main difference with this study is that rule-based approaches primarily operate on more complex discrete products rather than continuous geometric parameters, thereby preventing unrealistic design configurations. Regression-based parametric LCA uses statistical models to predict environmental impacts by replacing heavy data with proxy metrics (Jang et al., 2022). The method employs a black-box approach and an empirical input-output relationship, while the generic parametric LCA used in this study preserves the structure of the inventory and its systematic relationships. Meanwhile, feature-based LCA integrates impact calculation logic with digital engineering and design software, such as computer-aided design (CAD) and building information modelling (BIM) (Chen et al., 2017). It automates data extraction (e.g., material types, geometry, weight), allowing rapid LCA outcomes, as this method is the closest to the parametric LCA used in this study. The parametric LCA employed in this work provides logic in parameter selection and operates at the inventory construction level. It defines how inventories are expressed as a function of design parameters. Its implementation does not require specific software, statistical skills, or CAD integration, making it accessible as a first approach for manufacturing companies with high-mix products to replicate.

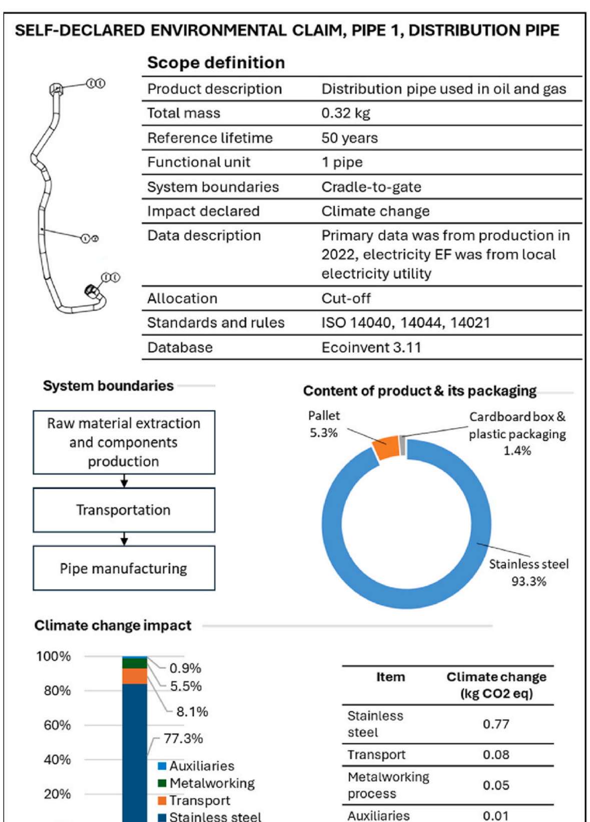

Fig. 8. Self-declared environmental claim as a service bundle.

4.1.2. *Evaluation*

To evaluate the proposed solution, the calculation results were compared to traditional LCA. Sensitivity analysis and Monte Carlo Simulation were also employed. The comparison with traditional LCA was also conducted on the impacts of the total pipes manufactured within one financial year. Since climate change impacts on materials, transportation, and auxiliaries were the same between parametric and traditional LCAs, Table 1 focuses on the impacts from the manufacturing process, shown in kg CO_2 eq.

When the results of four pipes were compared on the sum of individual pipes, the total impact of the parametric LCA was 59% of that of the traditional LCA. Meanwhile, when the comparison covered impacts by total quantity, parametric LCA resulted in 13% higher impacts than traditional LCA. Post hoc LCA is suitable if the study aims to calculate the overall impacts of the manufacturing process in a single financial year. The application of allocation will also ensure that the overall impacts resulting from summing individual impacts match those of the whole manufacturing process, since each input is associated with the pipe's weight. However, the individual result may be less accurate, as the energy consumption of metalworking routing depends on the running time and pipes' geometry (wall thickness and diameter) (Khan, 2025; Nur et al., 2021) , although weight is linked to wall thickness.

Sensitivity analysis shows differences in the most sensitive inputs. Similarities were observed across the four pipes, with compressor 1's electricity consumption as the most sensitive parameter (Fig. 9). Differences in the sensitivity results are also affected by different routings in each pipe, as shown by pipe 1, which did not undergo welding, bending, or pressure testing. As the diameter and wall thickness increased, the sensitivity of the most sensitive parameters to the rest decreased (as shown by pipes 3 and 4). The most critical variables will require greater attention to ensure their accuracy during data collection and analysis to make robust conclusions.

Results from the Monte Carlo simulation are shown in Fig. 10 and follow a normal distribution. There was a variability in the statistical indicators derived from the Monte Carlo simulation across four pipes (Table 2). The bigger the pipe, the better the statistical indicators, as they showed lower coefficients of variation and kurtosis. It can be inferred that the model for larger pipes is more accurate and less likely to produce outliers.

4.2. *Discussions*

The results of the study showed that parameterizing LCA through a product configurator could support PSS implementation in industries with a high-mix products by providing add-on services on climate change impacts and utilizing digital platforms to improve information flow and sustainability. Conventional processes will be resource-intensive, requiring significant manual labor and LCA expertise. The nature of the product family can be exploited, since the products are related and share a common manufacturing process. The similarities in the manufacturing process make it suitable for parametric LCA, in which

Table 1
Comparison of parametric LCA (P) and traditional LCA (Trad).

Item	Pipe 1		Pipe 2		Pipe 3		Pipe 4	
	P	Trad	P	Trad	P	Trad	P	Trad
Compressor	0.049	0.007	0.638	0.058	1.68	0.37	4.63	2.67
Cutting	0.000	0.004	0.001	0.033	0.01	0.21	0.06	1.53
Bending	0.006	0.002	0.015	0.019	0.07	0.12		
Welding			0.112	0.332	0.88	2.12	4.97	15.39
Pressure test			0.032	0.011	0.13	0.07	0.42	0.53
Drilling					0.01	0.01	0.16	0.09
Quantity	20,005	20,005	7574	7574	1213	1213	169	169
Impact (individual)	0.055	0.013	0.80	0.45	2.78	2.91	10.23	20.22
Impact (by quantities)	1094	250	6048	3427	3374	3524	1729	3417

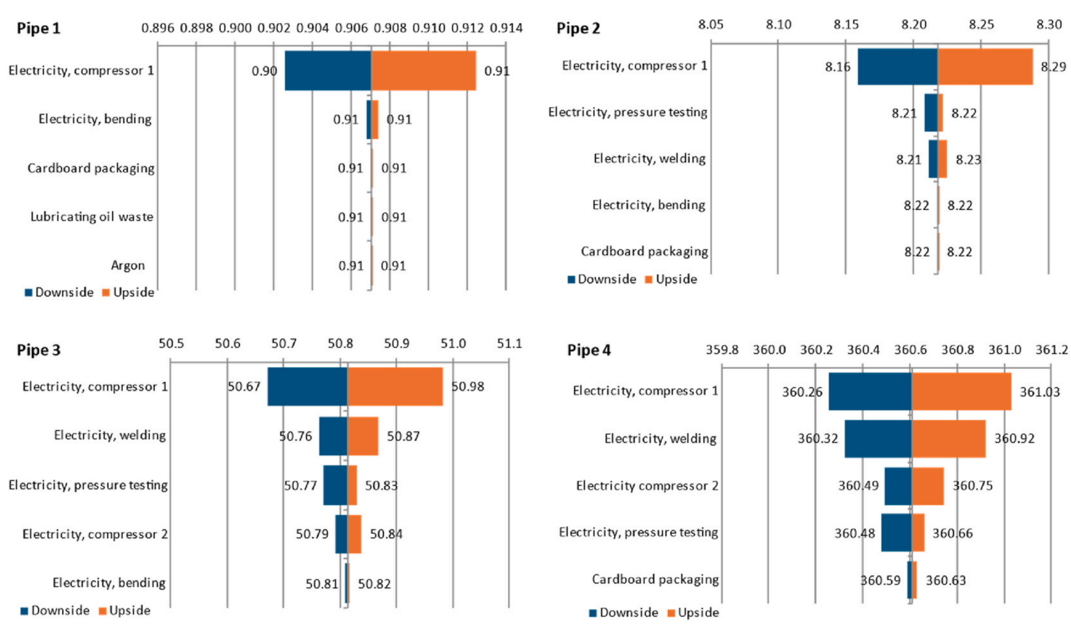

Fig. 9. Tornado chart of sensitivity analysis.

design parameters are directly linked to environmental impact data via mathematical formulas. Its implementation enables rapid calculation and real-time comparison of design alternatives, supporting evidence-based decision-making early in the planning phase. It also facilitates transparency by replacing fixed values with parameters and formulas, thus increasing the reproducibility and replicability of results. To perform the assessment using parametric LCA, a different set of data was required than for traditional LCA. As the total outcomes were calculated through allocation and parameterization, some fixed values (e.g., product weight or transport distance) are still needed.

Implementing the artifact will change value creation in some ways. First, it shifts the reactive approach of environmental accounting to a proactive one. Companies mainly use traditional LCA to calculate impacts after products are finalized, making it a retrospective audit rather than a design input. The artifact will cause temporal shifts as environmental performance becomes visible during the design phase, changing LCA from a compliance activity into a design tool. Second, providing results at the configuration level can make companies stand out. Traditional LCA often assesses a product family by selecting a representative product or averaging product inventories. While reducing manual workload, it can obscure the actual impacts of the product variant. The artifact enables impact calculations at the configuration level for a specific product, so companies can distinguish service offerings based on environmental aspects. Environmental data becomes an operational variable that can be used for contract design or negotiations. Lastly, the artifact enables scalable environmental accounting. The manual workload of accounting for environmental burdens for each product imposes a practical limit on how many products companies can assess within a single financial cycle. The artifact removes the limitations and allows the calculation to reproduce across all product variants. Environmental disclosure will shift from periodic reporting to operational outputs generated alongside production data.

One core of servitization is adding knowledge-based services to physical products to increase value (Baines et al., 2007). Within the context of this study, it poses a challenge to shift to product-related services, since information about the environmental performance of each product variant is unknown. Parametric LCA resolves this knowledge asymmetry by generating product-specific, delivery-time environmental data and real-time environmental data. It aligns with information good theory (Shapiro and Varian, 1999), where LCA results can be considered information good as their generation requires little cost once the initial parametric model is developed. The manufacturer is not only a pipe supplier but also an environmental data provider, which supports additional value creation (Baines et al., 2007). The company becomes a knowledge resource generator in a service innovation project (Xu et al., 2025), where customers can use the data to feed their own LCA and reporting, as well as to make procurement decisions. Parametric LCA also has the potential to enable data-as-a-service, where environmental data can be seen as a mini digital twin of the manufacturing process from an environmental perspective. Each

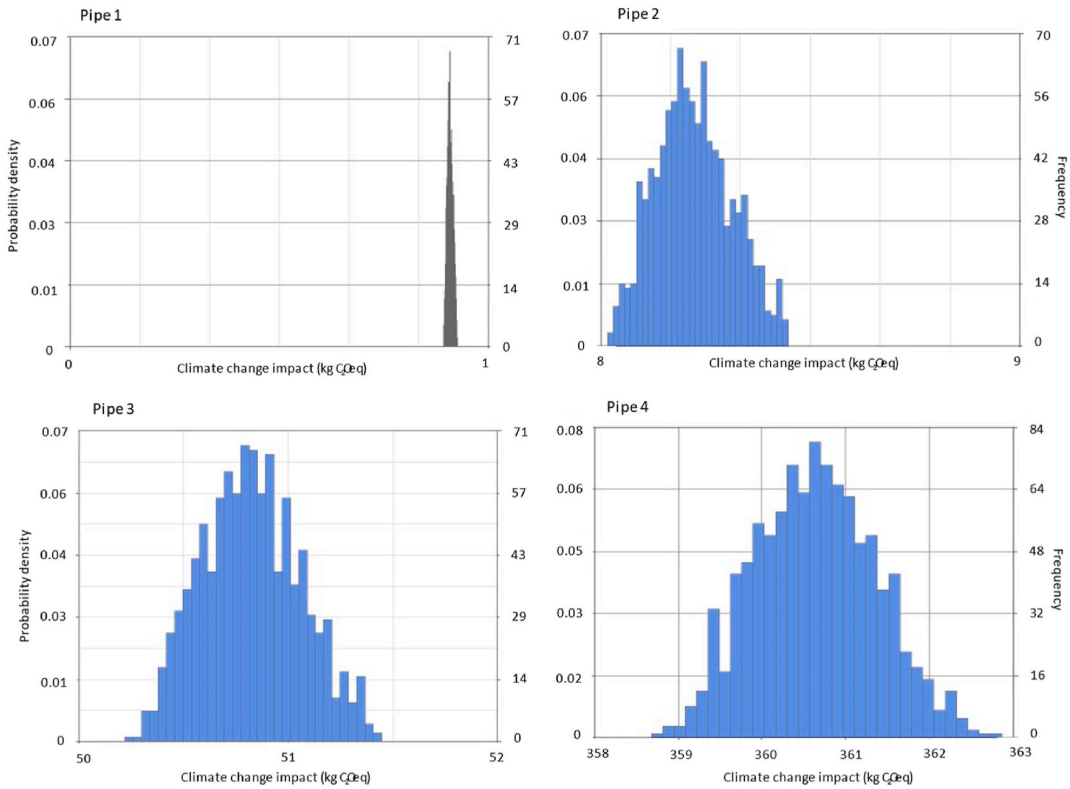

Fig. 10. Results of Monte Carlo simulation.

Table 2
Statistics indicator of Monte Carlo simulation.

Statistics indicator	Pipe 1	Pipe 2	Pipe 3	Pipe 4
Mean LCA[a]	0.92	8.36	51.10	361.15
Mean	0.91	8.22	50.82	360.64
Standard deviation	0.0069	0.0909	0.2362	0.7276
Coefficient of variation	0.0076	0.0111	0.0046	0.0020
Kurtosis	−0.603	−0.557	−0.499	−0.403
Maximum	0.925	8.447	51.445	362.859
Minimum	0.893	8.016	50.221	358.679
Range	0.033	0.431	1.224	4.181

[a] Average results from LCA calculation.

product variant has an automatically generated digital environmental profile. Parametric LCA is, in theory, a methodological core for digital service innovation in quantifying impacts in manufacturing, while the configurator serves as a platform for parametric LCA to operate. The service dimension of the artifact also extends beyond sustainability information, as the relationship between companies and customers can change. Companies capable of providing operational-level environmental data can formalize it as part of contract negotiations. The artifact allows the companies to make credible, configuration-specific calculations rather than aggregate numbers retrospectively. It becomes a selling point where companies offer impact quantification as part of the contract specifications. The artifact also supports supply chain transparency, as customers who purchase multiple product variants will obtain tailored results for specific impacts for each variant rather than average values for the product family that those variants inherit.

The contribution of the artifact can be distinguished from LCA automation and PSS standpoints. On the LCA side, the artifact's contribution addresses methodological aspects where traditional LCA can be too slow, labor-intensive, and inflexible in dealing with product variants. A parametric LCA model solves this by defining inventory logic for parameterization and propagating it across the product family automatically. The work is particularly useful for LCA practitioners and engineers dealing with product variants and environmental assessment. It delivers efficiency, flexibility, and reproducibility that are independent of PSS practice, enabling companies to implement parametric LCA for automation with or without PSS in place. Moreover, parametric LCA is key to handling different levels of data granularity, enabling environmental performance to be adjusted seamlessly (Douziech et al., 2024). The configurator addresses the need to build an individual model for each product variant, transforming a manual, resource-intensive task into an automated workflow. As Wiezorek and Christensen (2021) argued, configurators are the only way to solve environmental assessment challenges in mass customization. Unlike a standalone tool, operation integration of the configurator allows direct retrieval of running time from manufacturing routing information to ensure the environmental data is as accurate as possible. The business that intends to integrate sustainability information into a configurator could face challenges regarding the complexity of inventory and impact assessment (Wiezorek and Christensen, 2021). Hence, the implementation of parameterized LCA is specifically intended to address variability and enhance adaptability (Arias et al., 2025). Meanwhile, within the context of PSS, it addresses the issue of companies that sell bundles of products and services needing to calculate, report, and contractually commit to environmental assessments at the configuration level.

A variety of sustainability tools exist, each with a primary function. They can be categorized as traditional LCA software (SimaPro, openLCA, GaBi, Umberto), construction-focused LCA (One Click LCA, EC3 tool, Ecochain), carbon footprint-oriented (Persefoni, Watershed, Carbonfact), and AI-powered calculators (MyCarbonAI, Climatiq, CO2 AI). Those are examples of digital tools that operate differently based on user demographics (LCA experts vs non), sectors (apparel and footwear, food and beverage, construction), and methodology or framework (LCA, EPD, GHG protocol, corporate or product-level accounting). Traditional LCA tools offer high specificity at high manual labor, while carbon accounting tools provide scalability while costing the specificity. A parametric approach bridges these trade-offs by enabling both specificity and scalability in parallel. Existing tools are mainly standalone sustainability software, while the proposed solution is a calculation built on top of existing manufacturing data. Nevertheless, the existing tools have established validation, even verification and certification flow particularly for EPD calculation. They also have built-in features to assess uncertainty using the Ecoinvent pedigree matrix to perform Monte Carlo simulations. The proposed solution is no replacement for existing LCA tools. The choice of tool or method depends on the calculation's goals and implementation. It offers complementary options to achieve automated, product- and time-specific LCA for high-mix manufacturing, which can be delivered as a digital service component bundled with physical products. It transforms regulatory compliance into product features.

4.3. Academic and managerial implications

On the theoretical level, the study formalized the parameter selection, which is governed by the traceability of a direct link between inventory and configuration and by the distinction of auxiliaries that are affected by configuration but not directly parameterizable, resulting in a hybrid boundary structure. At the same time, the methodological contribution also comes with challenges. While traditional LCA lacks adaptability and flexibility, its longstanding development provides standardized methods. Meanwhile, there is a significant gap regarding a standardized guide for parameter and inventory development in parametric LCA applications, which this study addressed by emphasizing traceability and direct links to the inventories for some configurations to serve as parameters. Lack of standardization also hinders fair comparison across research on similar products or activities. Moreover, computing parametric LCA requires specific tools to handle the workflow that combines data inventory, parameters, and mathematical equations. The use of Excel in this study was to ensure flexibility and accommodate the mathematical formulas.

At the operational level, the study illustrated how manual effort is reduced in calculating environmental impacts across product variants, the capability to recalculate the impacts when design parameters change without rebuilding the model, and the ability to perform LCA calculations for non-specialists. The study offers strategies for companies facing increasing regulatory requirements to disclose product-level environmental impacts, especially in high-mix environments. It resolves sustainability-related issues, such as facilitating rapid calculations for sustainability reporting, eco-design and early-stage decisions, process parameter optimization, and handling uncertainties. This solution addresses some of the use cases presented by Zhang and Seuring (2024) and proposes a practical approach to efficiently generate environmental product declarations required for ESG reporting (Frecautan and Nita, 2022). Implementation of parametric LCA can also support companies in performing environmental assessments without requiring extensive resources or expertise. Nevertheless, its initial implementation needs tailored solutions to develop parameters, inventory data, and computational workflow.

The sturdy's implications map directly into the RQs. The finding indicates that parametric LCA enables PSS beyond system automation by generating configuration-specific environmental data at the granularity required by customers. It shifts environmental performance into a service attribute rather than a retrospective assessment. The finding also indicates that the type of data needed for artifact implementation is not exhaustive. It is essential to distinguish between configuration-driven parameters that operate at the operational level and auxiliaries, for which the aggregate behavior is sufficient for empirical approximation. The Monte Carlo shows that the two-layer data structure is sufficient for the company's application.

5. Conclusions

The study has demonstrated methodology for parametric LCA for ex-ante calculation in high-mix manufacturing with documentation of parameters selection, auxiliaries impacts, and uncertainties assessment. It offers knowledge contributions in the manufacturing, servitization, and sustainability fields. First, it reconceptualizes parametric LCA as an enabler to shift product selling into product-bundle PSS in high-mix manufacturing. It connects LCA methodology with servitization theory. Next, the proposed solution also develops methodology to assess multi-process parametric LCA for high-mix metal manufacturing which extends from the existing single-process manufacturing models. It employes geometry-based load factors to proportionally calculate environmental performance. Lastly, it offers methodology to incorporate foreground uncertainty assessment under data-scarce conditions by employing triangular distribution so that probabilistic sensitivity analysis can be calculated.

The solution also shows a deployable workflow that includes a proposed data model, a calculation schema, and governance. On the academic level, it means further development of parametric LCA, which is important for both theoretical design and manufacturing operations. It also promotes academic discourse on moving beyond traditional environmental reporting toward dynamic, data-driven PSS implementation. This study also contributes to the literature on sustainable supply chain management by showing how granular, variant-specific data can be generated without a manual model. The solution can be compared to traditional post-hoc LCA, static EPD documents, and generic product passports. The proposed parametric approach, connected to operational product family-level configuration, outperforms them in speed, effect resolution (granularity), and manufacturing system integration. This approach differs from earlier parametric solutions.

The study demonstrated a case company's product lines and their LCAs, and presented how the configurator contributes to analyzing GHG emissions throughout their life cycle. It shows the way to calculate the emission levels of the sample component varieties required for a complete product line. The configurator informs companies beyond material impacts, as the data can be used to manage sustainability through evidence-based decision-making in product development and procurement decisions. These results are encouraging for further development of digital solutions for sustainable operations and supply chains.

Despite its contribution, the study poses some limitations. Although the single case study is deemed appropriate, generalization may be limited to certain high-mix manufacturing. It may not be directly applicable to industries with different production logic such as continuous process manufacturing or high-volume standardized production. Furthermore, the application of the artifact depends on the digital maturity of companies where the configurator relies on existing manufacturing data. Consequently, the study assumes that industries have certain levels of digital readiness. The study also focuses on cradle-to-gate boundaries and climate change impact calculation. Future studies could apply the model to different sectors, expand system boundaries and impact categories. It could also focus on the parametrization methodology in which different parameters are selected from same system to support standardization and validate the results.

CRediT authorship contribution statement

Ahm Shamsuzzoha: Investigation, Writing – original draft. **Bening Mayanti:** Conceptualization, Formal analysis, Software, Validation, Writing – original draft. **Petri Helo:** Conceptualization, Investigation, Methodology, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130312.

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