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Bill of sustainability: integrating life cycle assessment into bill of materials and operations for sustainable manufacturing

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ABSTRACT

Managing sustainability-related data for a wide range of products systematically and efficiently is a challenge for manufacturing companies. While manufacturing execution systems (MES) and enterprise resource planning (ERP) systems maintain up-to-date information on process and raw material batches, this data is traditionally disconnected from environmental impact quantification. This paper presents the concept of the bill of sustainability (BOS), a framework that integrates a generic bill of materials and operations with life cycle assessment (LCA) to enable a product-portfolio-level system that can report product-instance-level sustainability data. Unlike conventional LCA, which operates post-analysis, the BOS framework facilitates environmental-informed decision-making during production and planning by mapping materials and operations to a standardised environmental impact database. The framework is validated through a software prototype and a case study on electric motor variants, demonstrating its ability to calculate climate change impacts across product configurations. The results indicate that BOS is scalable to handle high-variety manufacturing, connecting operational logistics and environmental accounting. The system has been piloted with a group of metalworking machine and electric drives companies, and the results have been reported.

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1. Introduction

The transition towards sustainable manufacturing has gained momentum in recent years due to increasing product diversity, tightening environmental regulations, and customer demands for environmentally responsible products. More companies are recognising the benefits of implementing sustainable initiatives ahead of regulatory requirements, as proactive actions can reduce the risk of sudden compliance costs and operational disruptions (Brown 2025; Kim 2018). Modern manufacturing is characterised by high-variety products, in which companies offer various product configurations to meet market demand. Nevertheless, increased product diversity complicates production planning, requiring suitable tools to manage product structures and their environmental impacts, particularly climate change impacts.

The severity of climate change and the urgency to curb it have led to global reduction targets and more stringent environmental regulations, such as the emissions trading system (ETS), carbon border adjustment mechanisms (CBAM), and the corporate sustainability reporting directive (CSRD) (Nordea 2024). Additionally, consumer preferences are shifting towards low-carbon

products (Feucht and Zander 2018), pushing companies to integrate sustainability considerations into production planning. One of the challenges in integrating sustainable manufacturing practices is quantifying the environmental impacts across the product life cycle. Life cycle assessment (LCA) provides a systematic way to evaluate impacts by accounting for all inputs and outputs throughout the manufacturing process, including upstream stages during material and component production, and translating them into meaningful impacts such as climate change (ISO 2006b, 2006a). A traditional manufacturing management system applies separate systems for production planning, such as bill of materials (BOM) or bill of operations (BOO), and for environmental impact quantification, such as LCA applications. The separation leads to inefficiencies: LCA analysts manually extract and build the data needed for environmental assessment from BOM and BOO, while production planners lack access to environmental information that can be useful for decision-making. For manufacturers offering high-variety products, conducting individual LCA studies for each variant becomes infeasible.

Hence, integrating environmental impacts into product planning is crucial. Companies are developing their

operations to build low-impact supply chains, which require connecting digitalisation with sustainable practices (Koh et al. 2023; Schilling and Seuring 2024). Some examples include digital passports for product instances (Abreu, Pereira, and Barata 2025) and digital twins for sustainability-related data (Werner et al. 2025). A framework that enables sustainability-based decision-making in production management will enable companies to improve, for example, by selecting low-impact materials, optimising operations and transportation based on environmental considerations, and reporting and complying with policies. This study aims to develop a bill of sustainability (BOS) in which environmental considerations are integrated into the bill of materials and operations to quantify environmental performance within production planning systems. The work is built on a generic bill of materials and operations (GBOMO), a tool to handle high-variety production planning that provides a structured way to represent product configurations and manufacturing (Jiao et al. 2000). Despite its advantages, GBOMO lacks integration of environmental aspects, leaving environmental assessment separate from the operational system and hindering sustainability-driven decision-making. The aim of the study is achieved by focusing on the following specific objectives: (i) linking GBOMO into the environmental impact database associated with materials or operations, (ii) developing a method to calculate environmental impact in the BOS, and (iii) testing the framework using case examples and climate change impact as illustration.

Current implementations of generic bills of materials, routings, and LCA are designed for material handling and environmental engineering. These solutions do not address the need to produce environmental impact statements for a high number of product variants in the supply chain. What is missing in current knowledge is a reference model for implementing such an information system architecture. This paper proposes a novel bill of sustainability concept for integrating a configurable operational structure with environmental information. The expected outcome of this research is a framework that enables manufacturers to make environmental-informed decisions during production planning, thereby advancing the broader goal of sustainable manufacturing and reducing carbon footprints.

2. Related works

2.1. Overview of BOM, BOO, GBOMO in manufacturing

A bill of materials (BOM) is a structural description of the parts required for manufacturing, assembly, and other operations. BOMs often combine various documents

and maintain version control of the product. Design, planning, production, and sourcing share versions of BOMs (Jiao, Simpson, and Siddique 2007). As-built-BOM refers to the version shipped from the factory, and as-maintained-BOM refers to the version used in later stages of the life cycle. BOMs support material requirements planning and inventory control for calculating the required parts at each time period. Cost accounting for production also relies on up-to-date BOMs. Version control of BOM documentation is used to track engineering changes in relation to production life-cycle management. Smart product platforms and extended product designs also rely on BOM structures (Zhang et al. 2025).

Managing product families with many variants or product platforms that share a significant number of parts across the portfolio requires a more advanced approach to BOM management. Generic BOMs extend the concept to handle rules and support large-scale product variants and options (Olsen, Sætre, and Thorstenson 1997), which are needed for mass customisation (Jiao et al. 2000). Applying GBOM solves the problem of managing end-product customisation and maintaining multiple, separately managed BOMs within the data structures.

A screenshot of a computer screen showing AI-generated content may be incorrect.

A Bill of Operations (BOO) refers to routings, which are the operations steps and their sequence used in production and assembly. Each operation may be linked to various resource types, such as machinery, human resources, tools, and software licences, along with their capacities. Bill-of-materials and routings are intercoupled, and attempts to merge them have been proposed (Tatsiopoulou 1996). However, in a multi-factory environment, where localised part versions and varying production facilities produce the same product (e.g. Miltenburg 2001), the implementation is often two separate entities managing both. Figure 1 illustrates an example of a data model for linking the bill of materials and bill of routing by associating resources, operations, and items in a sequence. To manage environmental impacts, De Benedetto and Klemeš (2010) proposed merging this information into an environmental bill of materials, but this approach overlooks the component's life cycle. A previous study also proposed a formalised method to integrate carbon emissions into the machining process by designing a carbon-emission process bill of materials (C-PBOM) (Zhou et al. 2018). However, it was intended to address a very specific aspect of manufacturing: the machining process. The study also focused only on carbon emissions, rather than the broader climate change or other environmental impacts that encompass different types of emissions.

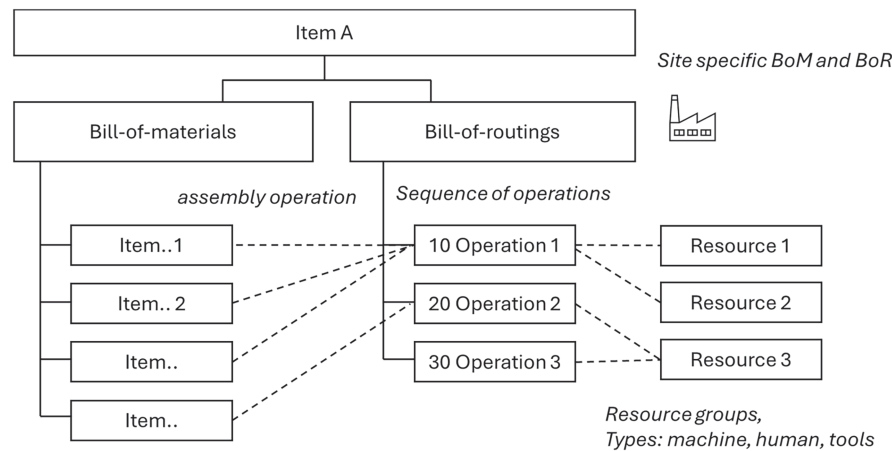


Figure 1. Data model example of bill of materials and bill of routings.

To manage product families with high variety, a generic bill of materials and operations (GBOMO) was introduced as an integrated model that combines BOM and BOO into a unified structure (Jiao et al. 2000). Rule-based configuration of product variants can reduce data redundancy and improve planning. Despite its capabilities in managing product variety and operations, it focuses predominantly on technical specifications, cost, and time without considering environmental aspects.

2.2. Life cycle assessment

Life cycle assessment (LCA) is an analytical method for evaluating the environmental impacts of products or services throughout their entire life cycle, from raw material extraction to disposal. It is based on ISO 14040 and ISO 14044, which define its application in four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO 2006a, 2006b). Traditional LCA (T-LCA) requires foreground data that originates from BOM (materials-related) and BOO (operation-related). Despite its rigour, it has limitations in a manufacturing context, especially in dealing with high-variety products:

- **Post-analysis.** LCA is commonly conducted after design completion or even after products are manufactured and distributed at the end of the financial year, limiting its influence on decision-making. To address the post-analysis issue, parametric LCA (P-LCA) should be implemented (Heijungs 2020) in combination with traditional LCA to obtain rapid calculation results.
- **Lack of integration.** LCA tools operate independently of the resource planning or execution system (ERP/MES), requiring manual extraction, mapping, and model building.

- **Variant inefficiency.** Each product variant requires a separate LCA study. The manual process of extracting and mapping data from BOM/BOO, followed by LCA calculations for each product variant, is resource-intensive and slow.

2.3. The need for an integrated framework

GBOMO can be seen as a production-centric system, capable of handling product variants. It provides information on material quantities and operational routing, which is considered foreground data in LCA, but lacks linkage to environmental factors. On the other hand, LCA can translate materials and routing inventory into meaningful environmental impacts, but it lacks the configuration logic embedded in GBOMO. The mismatch means that, in theory, a product family with 100 configurations will require 100 separate LCA studies. Relying on this approach is neither economically nor operationally viable. The problem is less about computation than about the structure of ERP design, which does not include environmental aspects, while LCA tools were built for a separate study.

The main aspects that cause a mismatch between the production management system and environmental calculation tools can be summarised as:

- **Temporal mismatch.** Production planning is continuous with specific orders and configurations, while LCA is typically conducted infrequently as a standalone study (e.g. a compliance requirement or customer request). It is often completed long after products have been distributed.
- **Data structure mismatch.** GBOMO manages data around material requirements and manufacturing routings. LCA tools organise data concerning the

environmental factors of different activities. These two systems will require suitable integration to work together.

- Data granularity mismatch. GBOMO deals with item-level and operational-level for components and process steps. LCA aggregates this information to simplify the modelling process, potentially resulting in a loss of granularity in variant-specific assessments. It can be a challenge for business suppliers to meet emerging regulations, such as the digital product passport (DPP), amid increased demand for product-specific environmental documentation (Zhang and Seuring 2024).

The traditional approach has limitations, and there is a need for better tools for operational solutions and rapid modelling at the product family level. Therefore, this study aims to integrate environmental factors into product planning by connecting BOM, BOO, and LCA through the proposed solution, the bill of sustainability (BOS).

3. Proposal development: bill of sustainability

The method of this study follows a design science approach for information systems (Hevner et al. 2004) to create and evaluate an artefact (the BOS framework and software implementation) that addresses a specific problem faced by the industry partners. The logic follows these steps: (1) collection of requirements, (2) analysis and design of the solution, (3) model development, and (4) assessment of the artefact developed.

- Collection requirement. The requirements were elicited through an in-person workshop on 25th October 2024 at the University of Vaasa, Finland. The workshop was organised to bring together a project consortium working on sustainable manufacturing. It involved 8 people representing four companies (one electric-drive manufacturer and three metal-working solutions), one university, and one project manager serving as workshop facilitator. These companies share common challenges: product variety, increasing customer demand for environmental documentation, and upcoming EU regulatory compliance requirements. The workshop followed a four-step procedure, including sharing individual goals, aligning collective goals derived from individual goals, needs mapping (what information or support each will need from others), and capability mapping (what information or support each can provide to others). The process ensured that all concerns were gathered so that each party could achieve their individual goals,

with potential support from others, while the collective goals were carried out as a group. Among all the collective goals, four requirements were identified: (1) automated environmental claim report (e.g. EPD-style reporting) without dedicated LCA expertise, (2) integration with existing ERP/MES systems, (3) updating environmental data when suppliers or processes change, and (4) traceability between product serial numbers and environmental declarations. This work particularly focused on requirements 1 and 3.

- Analysis, design and solution. Based on the requirements, a BOS concept was proposed by analysing the data structures of the BOM and BOO for a company consortium and mapping these data into a typical LCA inventory in accordance with ISO 14040/14044. The conceptual model was iteratively refined based on feedback from industrial partners.
- Model development. A tool prototype was developed using a web-based architecture. The software was piloted on an electric motor, a key component of electric drives. The application of the electric motor was conducted using secondary data due to confidentiality concerns, and the main purpose was demonstration. The implementation of the BOS framework involved mapping material codes to the Ecoinvent database and linking operation types to the energy consumption profile. BOS adds sustainability as a high-priority attribute to traditional production indicators (Di Lorenzo et al. 2025).
- Assessment of the artefact developed. This stage validates the proposed solution, specifically, it focuses on comparison with a traditional LCA application and uncertainty analysis. A validation case to test the calculation logic of P-LCA was applied using an anonymised company case.

3.1. Bill of sustainability

Traditional practice separates BOM/BOO/GBOMO from sustainability or LCA calculation. A practical example can be found in Amazon devices' product carbon footprint methodology, where they extract information from the PLM BOM and map it to an external LCA database to perform separate calculations (Amazon 2025). This study proposes a framework for sustainable manufacturing, called the bill of sustainability (BOS). BOS is an extension of the generic bill of materials and operations (GBOMO), which introduced the integration of the bill of materials (BOM) and the bill of operations (BOO) to maintain a seamless manufacturing process for products with high

variety. The idea of GBOMO is not novel; it was proposed to handle high-variety products (Jiao et al. 2000), in which documents provide complete information about the materials and operations required to manufacture a product. However, GBOMO does not account for sustainability despite containing crucial information about materials and operations, key components that are essential for calculating the environmental impacts of products or activities. BOS transforms BOM/BOO/GBOMO from a material inventory list and a sequence of operations into a decision-making tool in which sustainability is intrinsic rather than extrinsic. BOS will utilise information in the GBOMO as a basis for calculating environmental performance. BOS will still have GBOMO functionality, including details on customer order handling, engineering change management, production job scheduling, cost estimation, and coordinated material and capacity planning (Jiao et al. 2000), with the addition of environmental impacts calculation. The document can be used internally and externally. The former refers to manufacturing improvement, where BOS can guide the sustainability aspect of the manufacturing process by providing estimates of the impacts caused by each product at the design level. It allows designers or engineers to consider different materials, processes, power sources, and suppliers based on environmental performance calculations. Externally, the results can be used to meet regulatory requirements, as marketing materials for customers, or even as an additional service provided by the company to customers if it is a B2B business.

Developing BOS means expanding GBOMO to: (i) include processes or materials that are not yet present in the GBOMO but are necessary for impact calculation and complying with LCA principles, such as transportation or auxiliaries, (ii) integrate the LCA database for EFs extraction that enables impact calculation, and (iii) develop a system to calculate, store, and retrieve the environmental impacts. EF is a representative value that quantifies the amount of pollutant or impact categories per unit of product or activity. The values are extracted from LCA databases such as Ecoinvent or GaBi. Auxiliary inputs, such as packaging use, should also be identified for LCA completeness. All those inventories are then assigned relevant EF for impact calculation. A summary of the process is shown in Figures 2 and 3.

BOS reconceptualises how environmental information should be structured and maintained within manufacturing information systems. What BOS offers can be boiled down to the following aspects.

- BOS manages environmental impacts as configuration-based attributes rather than as static product properties. Just as GBOMO allows material quantities and

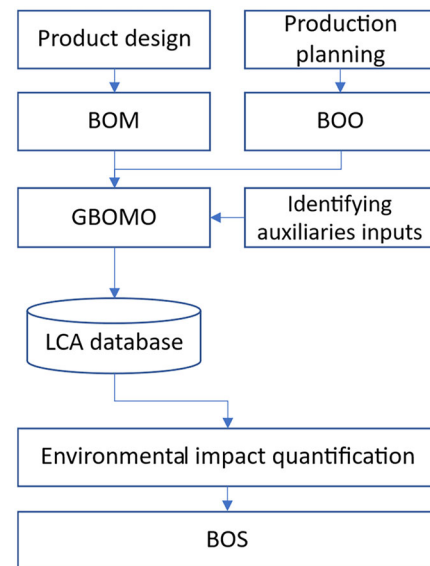


Figure 2. Summary of BOS development.

operation sequences to vary based on configuration rules, BOS translates these rules into environmental impacts.

- BOS maintains environmental data at the same level as production data. Traditionally, environmental data is stored in LCA tools or spreadsheets, while BOM and BOO are stored in ERP and MES systems. BOS will consolidate these within a unified system in which environmental factors are directly linked to material inputs and process operations. It enables rapid impact calculation as products are configured.
- BOS creates two-way traceability between product instances and environmental impacts. BOS can generate product-specific environmental documentation linked to a product's serial number or identifiers, enabling variant-level tracking throughout the product life cycle. It addresses emerging regulatory requirements and customer demand for product-specific impact rather than average environmental data.

The study contributes to the development of the bill of sustainability (BOS), a framework that extends ERP operations by integrating product-level environmental accounting alongside BOM and BOO through parametric LCA (P-LCA) for a configurable impact calculation method. P-LCA is implemented by extracting routing runtime information from BOO to enable a dynamic, flexible impact calculation process that generates immediate results rather than a retrospective one. The present demonstration concerns only the impacts of climate change; however, the approach is generalisable to additional categories, and this extension has been left for future work. Here, the operationalisation of P-LCA is

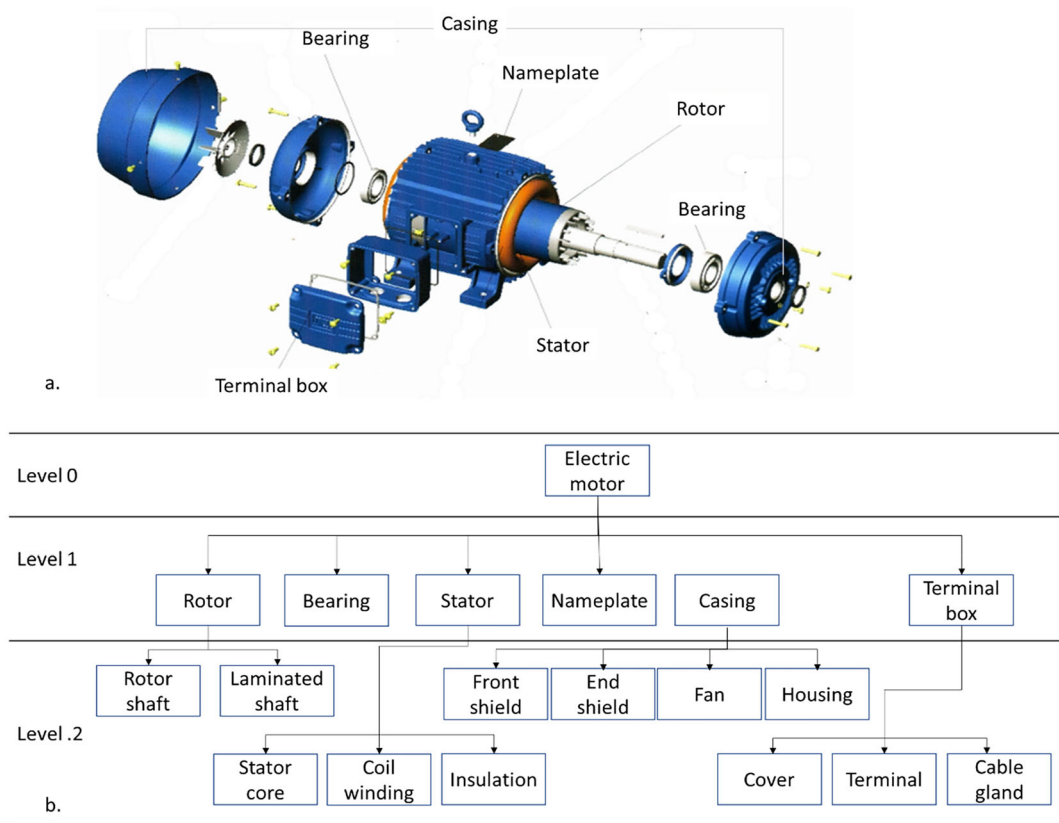


Figure 3. (a) Example of an electric motor, (b) BOM structure.

introduced using BOO runtime data within the manufacturing context. The tool also demonstrates how to automate EPD-style reporting generation for self-declared environmental claims. EPD-style reporting refers to a self-declared environmental claim document generated using the tool in the format and requirements of an EPD report. The report should be independently verified to qualify as EPD. Throughout this paper, 'EPD' refers to a self-declared environmental claim.

Two case examples were employed as illustration and validation layers. A hypothetical electric motor is implemented to demonstrate the operationalisation of the BOS framework, including the mapping process and EPD reporting covering cradle-to-gate boundaries. For illustration, each element should be presented in detail; hence, a hypothetical case is used, as it is non-exhaustive and does not pose a confidentiality issue. The validation layer employs a case industry partner that manufactures metalworking solutions. It validates whether P-LCA, the method that enables rapid calculation during the planning phase, can generate credible results compared to traditional LCA. It focused on the manufacturing stage, since gate-to-gate is where companies implement the method. Climate change impact was selected to illustrate the outcomes. A single impact was used, since the calculation principle was the same across all impact categories

in Ecoinvent EN-15804, and it was not possible to show how it applied to each impact category individually.

3.2. Impact calculation: traditional and parametric LCA

Traditional LCA refers to the LCA we commonly know, a retrospective assessment in which all inputs and outputs are derived by applying physical allocation, dividing annual values by total mass. Parametric LCA (P-LCA) enables prompt impact calculation during the planning phase, unlike traditional LCA, where calculations are usually conducted at the end of the financial year, with all inputs and outputs commonly assigned to a product using physical allocation. P-LCA does not employ fixed values; instead, it applies parameters and mathematical formulas to derive environmental impacts (Heijungs 2020). P-LCA has been implemented previously, especially in the building and construction sector, due to environmental requirements and the complexity of building design data (Arias et al. 2025). The application is a departure from static, traditional LCA, enabling the flexible, dynamic nature of LCA calculation. The calculation in BOS combined P-LCA and traditional LCA as

shown below.

$$\text{Total impacts: } CC_i = CC_m + CC_t + CC_{rout} + CC_{aux} \quad (1)$$

The impacts of product i (CC_i) are the result of impacts from materials (CC_m), transportation (CC_t), routing (CC_{rout}), and auxiliaries (CC_{aux}). P-LCA is used to calculate the impact from routing, while the remaining impact is calculated using traditional LCA. The impacts are calculated by multiplying the emission factor (EF) with life cycle inventory. EF is a coefficient that converts activity or product into a meaningful environmental impact.

$$\text{Impacts of material: } CC_m = \text{Weight} \cdot (EF_m + EF_{up}) \quad (2)$$

CC_m is the impact of material production (e.g. aluminium), *Weight* refers to the material weight (kg), EF_m is the emission factor for producing the associated material (kg CO₂ eq/kg), and EF_{up} is the emission factor associated with upstream processing (e.g. metalworking to transform aluminium into premade parts).

$$\text{Impacts of transport: } CC_t = \frac{\text{Weight}}{1000} \cdot \text{Distance} \cdot EF_t \quad (3)$$

CC_t is the impact of transportation, *Weight* (kg) refers to the transported goods, which is divided by 1000 to convert it into tons for unit consistency, *Distance* (km) indicates how far the goods are being transported using a certain transportation mode, and EF_t is the emission factor associated with the transport modes (kg CO₂ eq/t-km).

$$\text{Impact of routing: } CC_{rout} = \frac{\text{Runtime}}{60} \cdot El \cdot EF_{el} \quad (4)$$

CC_{el} is the impact of electricity consumption during the manufacturing stage, which is parameterised. *Runtime* indicates the length of operation (minutes) that is divided by 60 to convert it into hours, *El* refers to the power drawn by the equipment (kW), and EF_{el} is the emission factor of generating electricity (e.g. kg CO₂ eq/kWh).

$$\text{Auxiliaries and waste: } CC_{aux} = \text{Weight}_n \cdot EF_n \quad (5)$$

CC_{aux} is the impact from other inputs or output (e.g. lubricating oil, waste), *Weight* refers to the weight of associated input or output (kg), and EF_n is the emission factor (kg CO₂ eq/kg).

4. Validation case: metalworking solutions

Before illustrating the BOS framework, this section validates the logic behind rapid calculation using P-LCA. It utilises anonymised cases from a partner company offering a metalworking solution. The main module weighs

75 tons and consists of a loading table (1.5 tons), loading unit (3.5 tons), SG machine (12 tons), shear (15 tons), centreing unit (3 tons), and bending unit (40 tons). The company provides data for one financial year, enabling comparison between a full traditional LCA and a P-LCA. The inventory can be categorised into three groups: parameterised input, work by third party, and auxiliaries. Work by a third party indicates that metalworking and annealing processes were performed at a nearby manufacturing facility. Parameterised input covers assembly, painting, and factory acceptance test (FAT). In traditional LCA, total electricity during the manufacturing process is allocated based on product mass without differentiating between routing processes; meanwhile, P-LCA employs running time and power drawn during the process. The functional unit was a single product (e.g. a main module or variant module) with gate-to-gate boundaries, using the parameter values shown in Table 1.

The calculation showed differences between P-LCA and T-LCA (Table 2). For the main module, P-LCA resulted in an 8.2% higher impact than T-LCA. With the variant module, T-LCA was 2.1% higher than P-LCA. The contrasting pattern indicated that each module affected the calculation differently and the P-LCA's flexibility came at a cost. Although P-LCA is flexible and dynamic, it is not standardised, unlike T-LCA under ISO 14040/44. The lack of standardisation causes uniformity issues in parameter selection and in how parameters should be defined. Practitioners may set different parameters even when working on the same system, leading to uncertainty and bias. Nevertheless, it can serve as an efficient tool for rapid calculation, optimisation, and eco-design. The calculation also confirms a previous study showing that auxiliaries' contribution is not significant even when the scope is narrow, gate-to-gate. In all four scenarios, the contribution of auxiliaries is less than 3%.

5. Illustrative case: electric motor

The P-LCA method has been validated against an industrial case in the previous section. The present case, an electric motor, serves as an illustrative demonstration of how the framework and the tool work to include environmental aspects in the manufacturing process. The calculation was conducted for one unit product from cradle-to-gate. Figure 3(a) shows an illustration of an electric motor and its components (Cezário et al. 2005). An electric motor 2.2 kW with a mass ranging between 18 and 23 kg was used as an example case (Electrotech Drives 2021; Inverter Drive 2013). The product can be simplified into several main components, including the rotor, bearing, stator, nameplate, housing, and terminal box, which are assumed to weigh approximately 21.27 kg

Table 1. Parameter values for metalworking solution routing.

Module		Assembly		Painting		FAT	
		Time (h)	Power (kW)	Time (h)	Power (kW)	Time (h)	Power (kW)
Main module	Complete	300	15	60	40	115	115
Variant module	Loading table	10	12.5	2.3	35	6	30
	Loading unit	25	12.5	4.5	35	12	43
	Shear	65	17.5	13	43	35	60
	Centreing unit	20	12.5	3.8	35	10	30

Table 2. Summary comparison of T-LCA and P-LCA on metalworking solution.

Manufacturing	Main module (kg CO ₂ eq)		Variant module (kg CO ₂ eq)		Note
	T-LCA	P-LCA	T-LCA	P-LCA	
Assembly	2557	664	784	269	Parameterised
Painting		354		136	Parameterised
FAT		1952		346	Parameterised
Metalworking	466	466	143	143	Third party
Annealing	1907	1907	585	585	Third party
Paint	77.2	77.2	24	24	Auxiliaries
Lubricating oil	21.7	21.7	6.7	6.7	Auxiliaries
Water	0.03	0.03	0.010	0.010	Auxiliaries
Cutting fluid	12.5	12.5	3.8	3.8	Auxiliaries
Metal scrap	0.04	0.04	0.011	0.01	Auxiliaries
Wastewater	0.05	0.05	0.015	0.01	Auxiliaries
Mineral oil waste	23.2	23.2	7.1	7.1	Auxiliaries

(Care Moon Contracting 2023; de Almeida et al. 2008; Fukuta 2024). The BOM structure of the electric motor is shown in Figure 3(b).

Tables 3 and 4 show the baseline manufacturing data as presented in the conventional BOM and BOO for the selected electric motor variant. The BOM table specifies components, materials, weights, quantities, and geographical origins. The BOO table structures the manufacturing process, runtime, and energy requirement. The illustrative case is hypothetical, but the estimated values are confirmed by company partner. These documents, which contain information for production and material procurement but lack embedded environmental data, show a disconnect between operational planning and sustainability.

In a traditional LCA, the information in Tables 3 and 4 will be extracted manually and combined with EF values (Table 5) to build the LCA calculation. All processes are commonly conducted as separate post-analysis, unrelated to production planning, once the products are already distributed.

5.1. Inventories mapping and calculation

Each material and routing has an associated emission factor (EF). For example, producing 1 kg of Nylon 6 emits 5.5 kg of CO₂ and causes a climate change impact of 9.12 kg of CO₂ eq. The former refers to the amount of the pollutant (CO₂), and the latter indicates the impact category (kg CO₂ eq.). In this work, the term is interchangeable with impact factor and environmental factor. To integrate environmental factors into BOO/BOM, a

mapping process is required. A pre-mapping approach was applied during which we reviewed and linked BOM items and BOO routings to the most suitable Ecoinvent activity indicated by UUID number. Companies in the manufacturing sector, especially metal manufacturers in our project, usually produce a range of products with similar characteristics. These product families share materials and manufacturing processes, so the overall inventory is not exhausted. BOM items are connected to material production; BOO items are mainly linked to the energy provider, and other necessary inventory can be added as well (e.g. transportation). Since it is a tailored solution, understanding how companies' supply chains work is important so that inventory is linked to the appropriate activity. Some materials may have more than one match for users to choose from, while still allowing manual searches directly within the database. The inventory mapping is then stored as master data within the BOS layer, enabling impact calculation. Setting up the solution requires an understanding of LCA knowledge; afterward, LCA expertise is not needed at the point of use. In this study, the mapping and calculation were presented using Ecoinvent 3.10 EN-15804.

5.2. BOS framework

The BOS framework was applied to add a sustainability aspect to the operational document. Each material and process was linked to the corresponding database using predefined rules. BOS connects materials, operations, and logistics data with environmental factors to generate climate change impacts. Table 6 presents the

Table 3. BOM structure of electric motor.

Level	Parent item	Component	Material	Weight (kg)	Quantity	Origin
0		Electric motor		21.4		
1	Electric motor	Rotor				
1	Electric motor	Bearing set	Low alloy steel	0.3	2	Germany
1	Electric motor	Stator				
1	Electric motor	Nameplate	Aluminium	0.05	1	Germany
1	Electric motor	Casing				
1	Electric motor	Terminal box				
.2	Rotor	Rotor shaft	Silicon sheet steel	1.5	1	Italy
.2	Rotor	Laminated shaft	Silicon sheet steel	3	1	Italy
.2	Stator	Stator core	Silicon sheet steel	5	1	Italy
.2	Stator	Coil winding set	Copper	1.2	1	Italy
.2	Stator	Insulation set	Polyurethane	0.3	1	Italy
.2	Casing	Front shield	Aluminium	1.2	1	Germany
.2	Casing	End shield	Aluminium	1.2	1	Germany
.2	Casing	Fan	Plastic	0.4	1	Germany
.2	Casing	Housing	Cast iron	6.5	1	Germany
.2	Terminal box	Cover	Aluminium	0.2	1	Germany
.2	Terminal box	Terminal	Copper	0.05	3	Germany
.2	Terminal box	Cable gland	Stainless steel	0.1	1	Germany

Table 4. BOO structure.

Operation	Runtime (min)	Energy (kW)	Applied to	Level	Waste
Coil winding	15	1.2	Stator core		
CNC machining	20	2	End shield		5%
CNC machining	20	2	Rotor shaft		5%
Painting	10	0.5	Housing		
Assembly	12	0.1	All		

Table 5. EFs values.

Item	EF	Unit	Note
Low alloy steel	2.33	kg CO ₂ eq/kg	Product
Aluminium alloy (AlMg ₃)	7.04	kg CO ₂ eq/kg	Product
Copper cathode	6.02	kg CO ₂ eq/kg	Product
Polyurethane	4.48	kg CO ₂ eq/kg	Product
Cast iron	1.70	kg CO ₂ eq/kg	Product
Stainless steel	5.36	kg CO ₂ eq/kg	Product
Plastic, PP	2.37	kg CO ₂ eq/kg	Product
Paint	3.93	kg CO ₂ eq/kg	Product
Electricity	0.15	kg CO ₂ eq/kWh	Product
Metalworking process, average	2.35	kg CO ₂ eq/kg	Activity
Plastic injection moulding	0.86	kg CO ₂ eq/kg	Activity
Wire drawing copper	0.58	kg CO ₂ eq/kg	Activity
Metal scrap treatment	0.07	kg CO ₂ eq/kg	Activity
Lorry	0.15	kg CO ₂ eq/ton-km	Activity
Ship	0.01	kg CO ₂ eq/ton-km	Activity
Silicon sheet steel	7.04	kg CO ₂ eq/kg	Product

BOS structure, providing a component-level breakdown of climate change impacts, attributing them to material production, manufacturing energy, transportation, and auxiliary inputs. As shown in Table 6, the final product weight differs from the original BOM in Table 3 because the BOS captures material loss due to the manufacturing process. Implementing BOS will also instantly identify the component with the greatest impact, as shown by the stator core, which contributes about 30% of the total impact.

To implement BOS, the calculation should combine P-LCA and T-LCA. Upstream processes concern material weight, upstream processing into premade products when applicable (e.g. metalworking, wire drawing,

or plastic moulding), and transportation, which can be found in the ERP system, allowing rapid calculation. For simplification, the impacts of upstream processing of different types of metals were calculated using EF of 'metalworking process, average' (see Table 5). At the manufacturing stage, P-LCA is implemented by parametrising the running time (see Table 4) to obtain electricity consumption, which can be converted into impact results (see Table 6, column Operation, Energy (kWh), and CC manufacturing). Meanwhile, physical allocation in traditional LCA is used to calculate impacts from auxiliaries (e.g. consumables or scrap) by employing updated historical data. Calculating auxiliary impacts using historical data

Table 6. BOS structure.

Level	Parent item	Component	Material	Total weight (kg)	Lorry transport (km)	Ship transport (km)	Operation	Energy (kWh)	*Other inventory (kgC material)	Climate change (kg CO ₂ eq)			
										CC transport	CC manufacturing	CC total	
0		Electric motor		21.3								160.94	
1	Electric motor	Electric motor Rotor					Assembly	0.02			0.003	0.003	
1	Electric motor	Bearing set	Low alloy steel	0.6	700	1200			2.807	0.072		2.88	
1	Electric motor	Stator											
1	Electric motor	Nameplate	Aluminium	0.05	700	1200			0.469	0.006		0.48	
1	Electric motor	Casing											
1	Electric motor	Terminal box											
2	Rotor	Rotor shaft	Silicon sheet steel	1.5	1997	715	CNC machining Waste*	0.64		14.077	0.470	0.095	14.64
2	Rotor	Laminated shaft											
2	Stator	Stator core	Silicon sheet steel	3	1997	715							29.09
2	Stator	Coil winding set	Silicon sheet steel	5	1997	715	Coil winding	0.25		28.155	0.940		48.53
2	Stator	Insulation set	Copper	1.2	1997	715				46.925	1.566	0.037	8.30
2	Stator	Front shield	Polyurethane	0.3	1997	715				7.921	0.376		1.44
2	Casing	End shield	Aluminium	1.2	700	1200				1.344	0.094		11.40
2	Casing		Aluminium	1.2	700	1200	CNC machining	0.62		11.261	0.143		11.50
2	Casing	Fan	Plastic	0.4	700	1200	Waste*		0.06				
2	Casing	Housing	Cast iron	6.5	700	1200				1.292	0.048		1.34
2	Terminal box	Cover	Aluminium	0.2	700	1200	Painting	0.11		26.304	0.777	0.255	27.34
2	Terminal box	Terminal	Copper	0.15	700	1200							1.90
2	Terminal box	Cable gland	Stainless steel	0.1	700	1200	Paint*		0.065	1.877	0.024		1.27
										1.255	0.018		0.78
										0.771	0.012		

is deemed sufficient, as the resulting impacts are commonly insignificant, as shown by the validation case and previous work (e.g. Mayanti 2023; Peng et al. 2017). Common agreement indicates that 5% is the average cut-off in impact contribution (Henriksen et al. 2019).

6. Software implementation

6.1. Software functionality

To implement a technical solution to collect and process data for the bill of sustainability, a software solution was developed. The development work is based on life cycle assessment and existing data from manufacturing execution systems, including materials, routing, and operations. The software stack has been implemented as a database-based solution with application logic and a web-based user interface, similar to enterprise resource planning software packages and manufacturing execution systems.

The workflow of using the software comprises the following steps: (1) creating a workspace for the product family, (2) creating a life-cycle model, and (3) customisation of the environmental product declaration template. In the first part, a BOS model for a product family is created as a workspace. The next step is to choose a suitable life-cycle model. The scope can be adjusted to cover phases from the product's raw material extraction, manufacturing processes, transportation, use, and ultimately the end-of-life phases – disposal or recycling. This includes level parameters describing the configurations for generating product variants. Using parameter-value combinations linked to resource consumption or process-step variability, differences between product variants can be accounted for when calculating various environmental impacts. The raw materials from the bill of materials and the processes referred to in the routing information need to be mapped to their environmental impacts. Figure 4 shows life-cycle creation, mapping, and parameter creation.

The inventory needed to conduct LCA is not always available in the database, and it is quite common to use proxy inventory or build a specific inventory based on what is needed. The example of the former is using a generic database such as chemical organic or inorganic when a chemical input is needed but is not listed in the database. In this study, a proxy database was used for market activity in metal scrap, with 'iron scrap' applied to all types of metal scrap. The latter refers to creating inventory, such as modelling zinc chloride from zinc oxide and hydrochloric acid. In our case, the input unavailability is related to processes from specific suppliers, namely steel suppliers that provide the most important material input, especially for metalworking solutions. A software feature

called 'Process catalogue' is designed so that the process or inventory can be built based on the products' impacts obtained from suppliers' EPD.

In the final step, the solution can generate an environmental product declaration for any product variant based on configuration rules. As product-family-level configuration rules are maintained in the system and the required process data is modelled in the bill of sustainability, the solution can generate a unique life-cycle report for each product instance. The generated report can be linked to production serial numbers or, alternatively, to a customer-order-specific identifier that can be traced in the later phases of the product life cycle. The green button inside the red box shown in Figure 5(a) is where users can click to create an EPD-style report. The button is inactive because the life cycle model is empty. Once the model is built, the button will become active and change colour.

The use of the bill of sustainability should be linked to managerial operations. For daily use, the configuration of new product variants is triggered by customer orders or customer inquiries via quotations. If the product configuration process is in place and connected to BOM and BOO, the raw materials and operation routings trigger a request to retrieve impact inventory values. These values are then linked with the calculation, and the BOS is generated in the data model. The impact results can be evaluated by the user, allowing the product configuration to be changed. Once the final configuration has been selected, a unique self-declared environmental product declaration can be generated. These documents are stored in the centralised repository and integrated into the company's production-quality management and other product-compliance processes. The generated variants of the declared product documents are used for continuous monitoring and improvement. Periodic managerial reviews can pinpoint the actual environmental impacts for different product markets and their significance for order fulfilment. The actions taken based on this could include supplier selection, production technology evaluations and energy sourcing decisions. In the design phase, the feedback may relate to material choices and a redesign focus from an environmental perspective. Figure 5 illustrates the managerial workflow of BOS as described from the end-user perspective.

6.2. Case application of an electric motor

This section demonstrates the practical implementation of BOS using software that automatically generates EPD-style environmental claims for configurable product variants. While the automation of report generation is a direct function of the software, the software's logic implements

a.

Electric motor

Create a workspace

Life cycles

Create a Life Cycle

Create a Parameter

EPD-reports

Processes

Process catalog

Flows

Process impacts

Template life cycle to copy (optional) (selecting a template will override the life cycle template selection)

None

Create a new life cycle

Life cycle name (required)

Automatic PCR (You can optionally link a PCR to this life cycle.) [Source library](#)

Life cycle template (required)

Std 2 phases

Phases in this life cycle template:

- Production
- Use

Create Life Cycle

b.

42CrMo4

Enter General Name

Search

Database search

3 options found. Select a Process...

3 options found. Select a Process...

steel production, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | EN15804GD, U (RER)

steel production, electric, low-alloyed | steel, low-alloyed | EN15804GD, U (Europe)

steel production, converter, low-alloyed | steel, low-alloyed | EN15804GD, U (RER)

AISI 304

Enter General Name

Search

Database search

1 option found. Select a Process...

1 option found. Select a Process...

steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | EN15804GD, U (RER)

c.

Electric motor

Create a workspace

Life cycles

Create a Life Cycle

Create a Parameter

EPD-reports

Processes

Process catalog

Flows

Process impacts

Add new parameter

Name

Value

Uncertainty

Description

Name

0

none

Description

+ Add

Clear

Input Parameters

Name	Value	Uncertainty	Description	Edit	Delete
n	75	none	Number of machine module produced in year	Edit value	Delete
rho_oil	800	none	Lubricating oil density in kg/m3	Edit value	Delete

d.

Back

Result: Hot rolled steel company xyz

Impact Results

Name	Value	Unit
EN15804 (EF 3.1) Global Warming Potential - biogenic (GWP-biogenic)	0.2	kg CO2 eq.
EN15804 (EF 3.1) Global Warming Potential - fossil fuels (GWP-fossil)	1.2	kg CO2 eq.
EN15804 (EF 3.1) Global Warming Potential - land use and land use change (GWP-luluc)	0.1	kg CO2 eq.
EN15804 (EF 3.1) Global Warming Potential - total (GWP-total)	0.6	kg CO2 eq.
EN15804 (EF 3.1) Global warming potential except emissions and uptake of biogenic carbon (GWP-100C/GHG)	0	kg CO2 eq.

Figure 4. Life-cycle creation (a), mapping example for BOM (b), input parameter (c), Process catalogue (d).

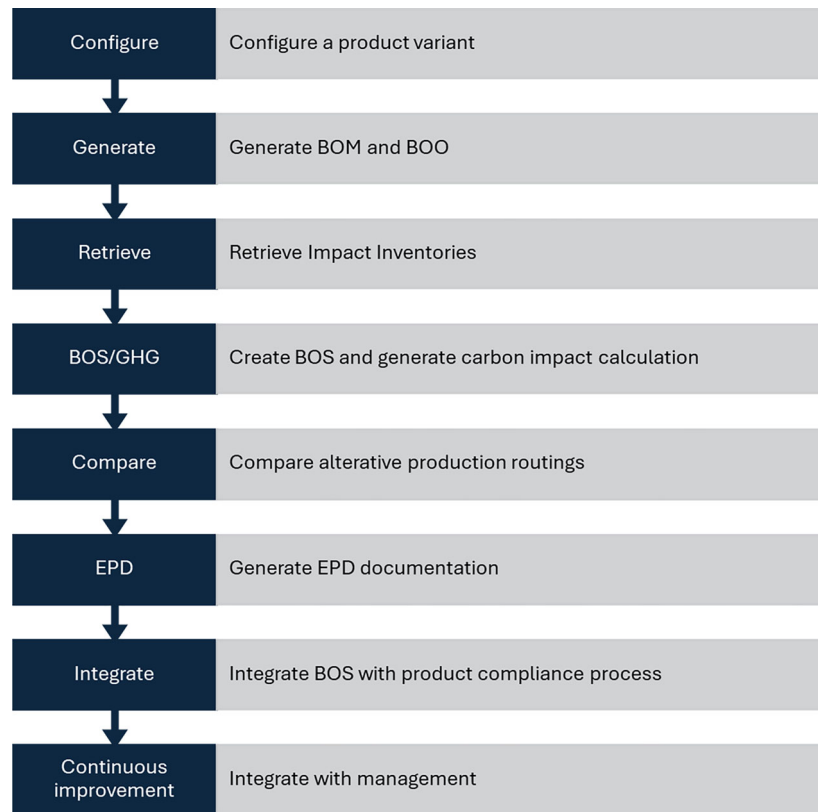


Figure 5. Managerial workflow of BOS.

the BOS framework that is shown in Section 3. This validation shows how the conceptual model of BOS enables a real-world application. The software demonstration used the same electric motor application. It will allow direct comparison between the manual and illustrative case in Section 3 and its automated, operational implementation. Figure 6(a) shows the workspace creation for different product families. Only one workspace can be activated at a time, and the bright green colour indicates the activated one. The life cycle for the electric motor was then created using relevant information from the GBOMO structure and executing impact calculation, as defined by Equations (1–4). Figure 6(b) presents the life cycle of the electric motor during the production stage, illustrated by the cable gland component, consisting of impacts from material (chromium steel), transportation (lorry and ship), and material processing (metalworking of chromium steel).

The impact table is also provided based on the LCA summary results. Figure 7(a) displays the climate change impacts of electric motor components (cable gland and stator core) following the logic of BOS, where the impacts are associated with materials, process, or transportation. The calculation results using the software can be matched with what is shown in Table 6, where the framework was

just built. After the life cycle is completed, EPD reporting can be created (Figure 7(b)). It requires information regarding the product, the company, and LCA. The process is guided, so users will know which information to fill in, and the report can be downloaded immediately.

This implementation validates two main aspects of the research: (1) Conceptual validity, where the software operationalises the BOS framework, showing that the proposed integration of product-specific data with LCA is technically and functionally feasible, and (2) Practical validity, in which the automated environmental claim reporting (EPD) contributes to a pressing industrial need for scalable sustainability reporting, demonstrating the applicability. The application of the electric motor case demonstrated the logic of the BOS framework, which can be integrated into the manufacturing system to deliver tangible improvements in sustainable manufacturing.

6.3. Sensitivity analysis of product family level

Having validated BOS functionality with a single electric-motor variant, this section demonstrates BOS's analytical capabilities at the product-family level by conducting a sensitivity analysis across multiple product variants. Product family-level analysis of a group of product variants and their respective BOS structures can yield

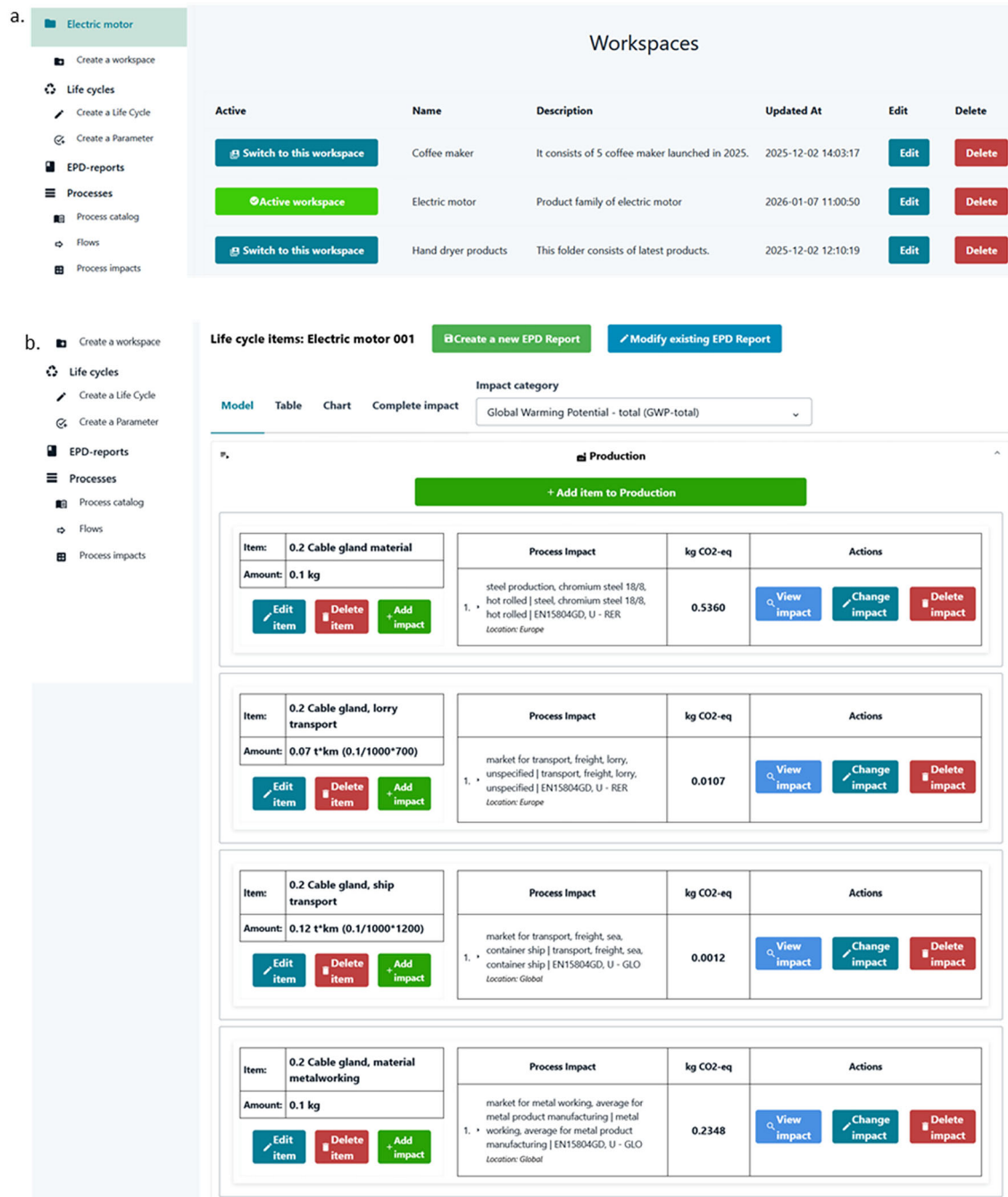


Figure 6. Life cycle of the electric motor illustrating the cable gland component.

information for product planners. The electrical motor example built as a generic bill of materials and combined with a configurator system can generate 216 different product variants based on combinatorial of five independent parameters: 3 options power ratings (75, 110, 200 kW), 3 options of efficiency class (IE2, IE3, IE4), 2 options of casing materials (cast iron or aluminium), 2 options of cooling system (liquid or air), and 6 options of service life (15, 16, 17, 18, 19, 20 years), yielding the total number of assessment combinations. Assuming

all variables are independent and using an even distribution, the configuration system generates a sample of 10000 orders (and variants) for a tornado analysis. The assumption resulted in the feasibility of any combination of parameters that is orderable. The uniform distribution reflects the absence of empirical order frequency translated into an equal prior probability across all options. In real life, certain product variants will be ordered more frequently than others. The use-phase emissions are modelled based on operational energy

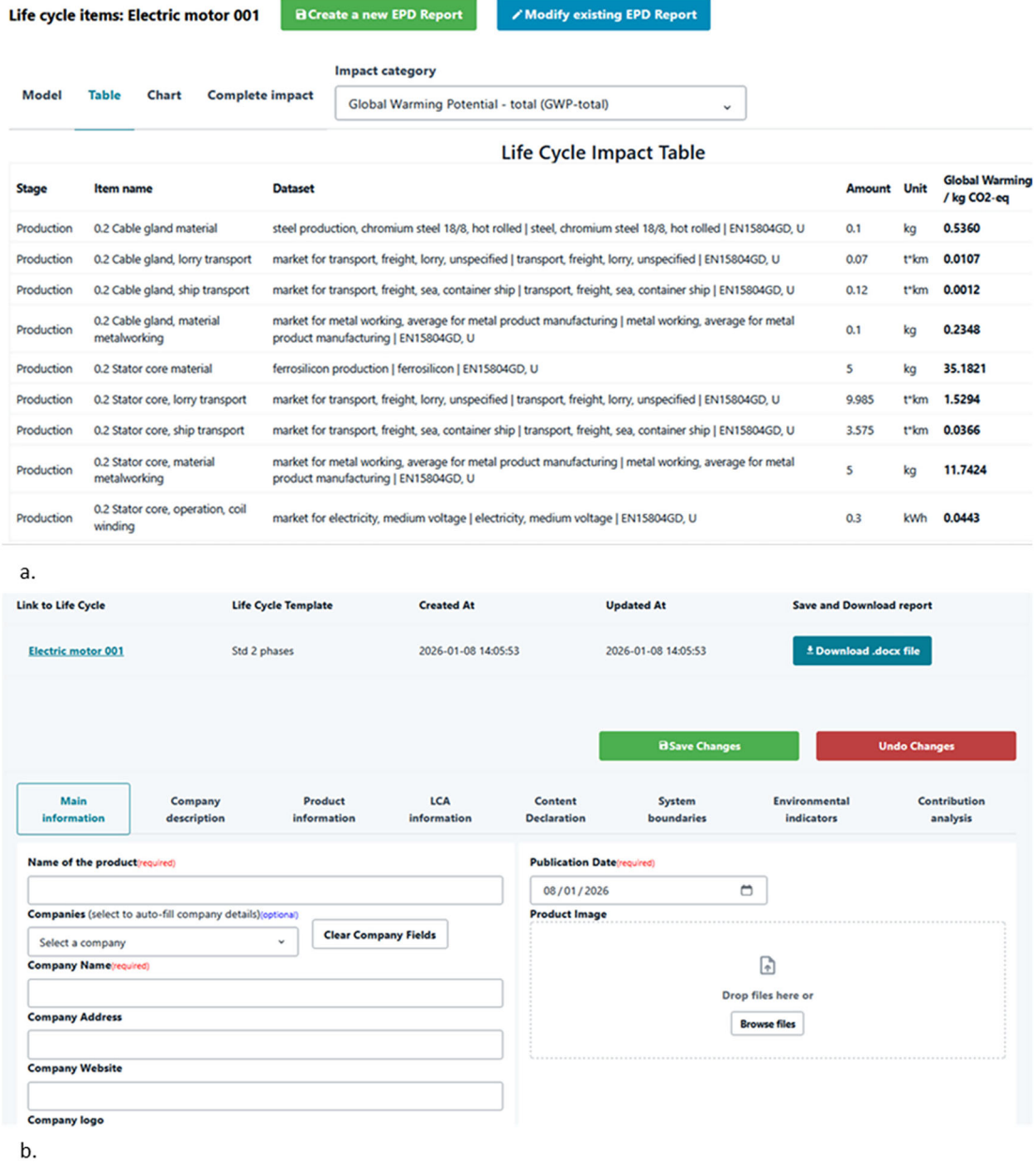


Figure 7. (a) Impact table of electric motor components, (b) The process of creating the EPD report.

approach (Equation 6). Annual electricity consumption is derived from power rating (kW), efficiency (%), and assumed operating time (hours). It is multiplied by service life (years) and emission from grid (kg CO₂ eq per kWh).

$$CC_{use} = \frac{\text{power rating} \cdot \text{operating time}}{\text{efficiency}} \cdot \text{service life} \cdot EF_{grid} \quad (6)$$

The climate change impact reported in the sensitivity analysis is the sum of cradle-to-use emissions which was an extension of cradle-to-gate by including use phase.

These two aspects are distinct: production emissions are driven by material composition and manufacturing process parameters from the BOM and BOO, while use-phase emissions are driven by operational parameters that are outside the manufacturing system boundary but are captured in the BOS configurator as product-level attributes. Use phase contributed significantly to the impact, considering the long service life and operating time of each product. The contribution can be more significant when the product is used in a geographical location with higher grid emissions. The analysis showed dominance of service life. The gap between service life (15 vs. 20 years) produces a 33% variation in cumulative

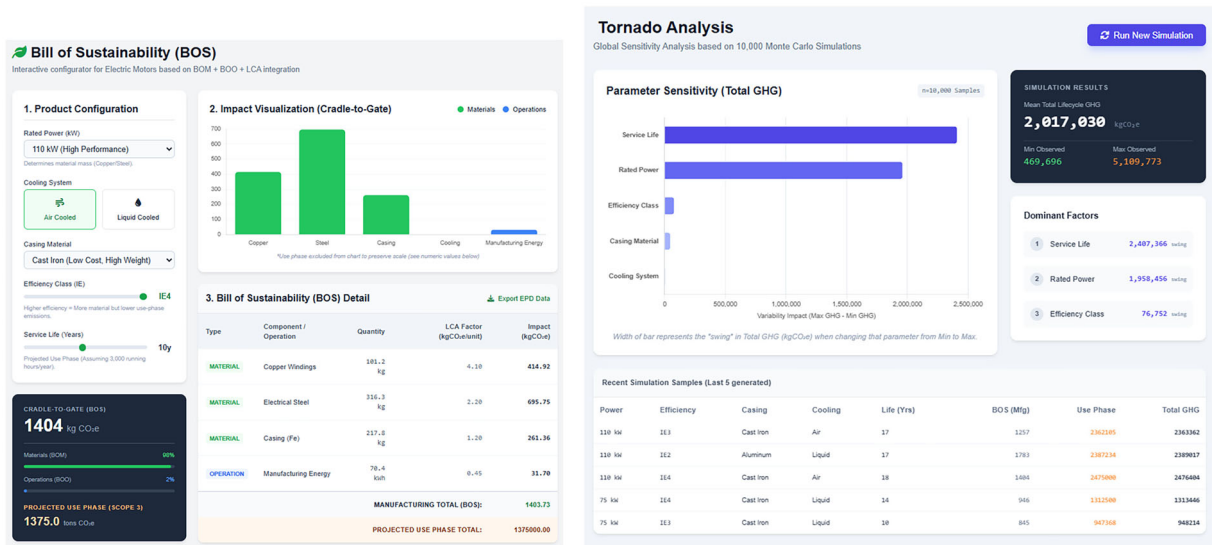


Figure 8. Generation of BOS variants and tornado analysis for parameter sensitivity.

use-phase energy consumption. Given that use-phase represents approximately 90–95% of total impacts, it translates into about 30% variation in total impacts. On the other hand, the efficiency class difference between IE2 and IE4 produces a 3–5% variation in annual energy consumption showing smaller total effect than the service life range. Figure 8 shows an example of product generation and the results of the sensitivity analysis.

The main purpose of sensitivity is to demonstrate the leverage points for designers. Another value-adding perspective it can show is handling the uncertainty when proxy datasets are used (e.g. iron scrap for mixed metal scrap) as case-specific inventory data has not been available or the use of ‘metalworking process, average’ for all types of metal during upstream processing for simplification. This results in variation in numerical precision rather than the validity of the BOS concept, and these assumptions can be improved upon following model updates.

6.4. Discussions

6.4.1. Comparative analysis: BOS and traditional methods

The application of BOS enables users to obtain environmental data for each order or product variant configuration at the planning stage, which can be used for internal or external purposes. Table 7 provides a summary comparison between the proposed approach and other established frameworks, namely LCA and GBOMO. The comparison shows how BOS addresses the gap in sustainability management in manufacturing.

Previous work presented a framework for rapid LCA/LCC using technology such as RFID (Trofimenko

et al. 2025). The work shares a similar objective with BOS in terms of immediate assessment, but it often focuses on gate-to-gate monitoring (activities that occur in the manufacturing facility), while the BOS framework offers a broader perspective, integrating suppliers and raw materials into the configuration logic. Another study proposed a carbon-emission process bill of materials (C-PBOM) that integrates emissions into the BOM (Zhou et al. 2018). The C-PBOM integrated a very specific emission from a specific process, namely, carbon emissions from the machining process. In contrast, BOS covers the product-family level, capturing climate change impacts from various greenhouse gases. It also provides flexibility to support both managerial decisions and detailed operational matters.

BOS's features align with emerging environmental requirements, such as DPP. A recent study argued that DPP is more than environmental information; it is a key to transitioning towards circular supply chain management (CSCM) (Zhang and Seuring 2024). DPP improves circularity and reduces emissions by enhancing traceability and transparency. BOS serves as a DPP foundation by linking a product's serial number to its associated environmental impact, which is missing in traditional LCAs. It can improve the trackability of products or parts throughout utilisation and help product recovery for reuse. This type of information allows the designers or engineers to prioritise the reused parts. It was reported that there is a need for product-tracking capabilities and quality assessment to support remanufacturing (Pérez et al. 2025).

As illustrated, the BOS framework links the disconnect between environmental accounting and product execution. In contrast with conventional LCA, which

Table 7. Summary comparison of LCA, GBOMO, and BOS.

Item	LCA	GBOMO	BOS
Purpose	Environmental impact quantification	Integrated product and production data	Integrated product, production, and sustainability data
Data granularity	Aggregated process level	Item and operation level	Item and operation level with environmental factors
Variant management	Separate study per variant	Generic structures with configuration rules	Configuration-based environmental calculation
Scalability for a high variety	Low (manual per variant)	High (designed for variants)	High (automated per variant)
Update frequency	Occasional (separate study)	Continuous (with each order)	Continuous (with each order)
Environmental calculation	Post-analysis	None	Integrated into the configuration process
Traceability to product instance	No (generic studies)	Yes (serial numbers)	Yes (serial numbers)
Data storage	Separate LCA software	ERP/MES systems	Unified system
Expertise	LCA	Production planning	Production planning and initial LCA setup
Decision support	Environmental (retrospective)	Operational	Operational and environmental
Application	Product development, certification, compliance, sustainability decision	Order fulfilment, inventory management	Product development, order fulfilment, certification compliance, sustainability decision

is retrospective, BOS enables rapid impact assessment. Compared with GBOMO, which lacks environmental data integration, BOS integrates impact calculation into the core planning. The integration enables automated generation of product-specific environmental claims, such as EPDs, and supports dynamic, environmentally informed decision-making during product configuration.

6.4.2. Contributions and managerial implications

The BOS provides a reference model for integrating environmental accounting with a manufacturing information system. It presents a non-traditional view of sustainability, commonly considered an extrinsic analysis, illustrating that climate change impacts can and should be embedded as configuration-based parameters. It moves towards instance-level data rather than average product data, enabling it to contribute to sustainable manufacturing. BOS also provides visibility into the supply chain's environmental impact, enabling companies to build strong networks to anticipate and adapt to changes in carbon prices, environmental regulations, resource scarcity, and ethical procurement practices. Supply chain resilience is considered a fundamental component of sustainability, in which companies should mitigate external challenges to sustain long-term profitability (Gardner and Colwill 2018).

On a practical level, BOS offers a scalable and automated solution for environmental reporting. It eliminates manual work that is prone to error when data is extracted from the EPR system to the LCA software. It also reduces the time, cost, and resources to generate an EPD report. Its ability to handle specific configurations ensures that environmental reporting on product-specific impact is up to speed. Industrial partners have reported during

the research project that the developed prototype system reduces manual work on various phases and enables quick comparison of different user scenarios. BOS also serves as a decision-support tool. It instantly identifies the environmental hotspot and the component that causes the highest impact, such as the stator in the case of an electric motor, providing engineers with a concrete target for improvement. It supports the circular economy transition, where companies incorporate reused parts to gain economic and environmental benefits (Pérez et al. 2025).

BOS is an enabler for sustainable manufacturing. The configuration will trigger the system to provide immediate feedback, allowing adjustments before finalisation. From a strategic standpoint, regular managerial reviews of the BOS library can highlight market sustainability trends. BOS can support high-level decisions concerning production technology, energy sourcing, and involvement in carbon-pricing markets. It also supports regulatory compliance, aligning with CSRD, CBAM or DPP. Climate regulation should be implemented early and gradually to reduce the risk of sudden compliance costs and operational disruptions (Koh et al. 2023; Lah and Kotnik 2025).

7. Conclusions

A need for a systematic way to build an information management system for sustainability data for production is increasingly important for companies operating in supply chains or providing manufacturing services. This paper has developed a concept of a bill of sustainability and demonstrated how BOS can be implemented across a wide variety of products. This extends the traditional bill of materials and routing to include sustainability-related impacts and life-cycle considerations. The paper

has demonstrated the technical implementation of the system and the rapid modelling application, and the solution has been validated through a real-life case. The BOS approach can be considered an operational enabler beyond reporting, as suggested by the low-carbon production and logistics systems framework by Lopes de Sousa Jabbour et al. (2021).

The proposed BOS framework presents a method for combining environmental assessment with manufacturing planning. Previous work, such as the environmental bill of materials, combined material data with the life-cycle concept, but it remained a static design tool. Meanwhile, BOS offers dynamic configurability and automation to handle product-specific impacts. It shifts sustainability from design analysis to an operational decision-support tool. Additionally, BOS contributes to the discussion on the life-cycle concept, which is typically applied using tools designed as separate engineering applications. These are often disconnected from manufacturing systems and enterprise resource planning platforms. The BOS framework connects configurable product structures with LCA databases.

The practical impact of the solution responds to several needs: (1) managers can use BOS structures for supply chain decisions, which refers to supplier selection, automation of EPD generation and participation in carbon pricing-based markets; (2) the BOS approach supports compliance with regulations such as corporate-level CSRD reporting and CBAM-related import customs fees. Meanwhile, the managerial implications of the study include demonstrating the potential of automating sustainability assessment and its practical implementation in the context of sustainable manufacturing. BOS provides environmental visibility during production planning, enabling decisions on supplier selection, material substitution, or process changes based on environmental factors rather than solely on cost.

While demonstrated through electric motor manufacturing, the proposed approach can be generalised to several industrial sectors that operate in manufacturing. The BOS architecture is built on the GBOMO structure, meaning it is not sector-dependent and can be deployed when configurable product and process management is required. Moreover, the framework is adaptable to varying regulatory and market demands (e.g. CSRD or CBAM) as well as product-specific data requests from customers. Future work based on the experience from this study is to test BOS across more industrial sectors and at larger operational scales. Other directions include implementing BOS to support production optimisation based on environmental factors and developing capabilities for scenario analysis.

Acronym list

BOM	Bill of materials
BOO	Bill of operations
CBAM	Carbon border adjustment mechanism
C-PBOM	Carbon-emission process bill of materials
CSCM	Circular supply chain management
CSRD	Corporate sustainability reporting directive
DPP	Digital product passport
EF	Emission factor
EPD	Environmental product declaration
ETS	Emission trading system
GBOMO	Generic bill of materials and operations
P-LCA	Parametric life cycle assessment

Author contributions

CRedit: **Bening Mayanti**: Data curation, Formal analysis, Methodology, Writing – original draft; **Petri Helo**: Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing; **Linda L. Zhang**: Conceptualization, Methodology, Writing – review & editing; **Roger Jiao**: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing

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Data availability statement

The data (access to software) that support the findings of this study are available from the corresponding author, PH, upon reasonable request.

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