

Article

Life Cycle Assessment of PLM System Scenarios: Sensitivity Insights from an Academic Use Case

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Abstract

The 2020s represent both the digital decade and the pivotal period in the fulfillment of long-standing commitments made by public, private, and institutional actors in favor of sustainable development. In the manufacturing context, Product Lifecycle Management (PLM) systems are used during the design phase to reduce product environmental footprint. However, only a few studies have thoroughly identified the environmental impacts associated with these technological solutions. This study proposes a sensitivity analysis of five environmental impact categories associated with two PLM system architectures and three mitigation scenarios. To this end, we use an engineering school as a representative PLM system case study, relying on the Life Cycle Assessment (LCA) methodology and leveraging specialized tools that enable the execution and comparative analysis of multiple LCA scenarios. Our results consistently identify the manufacturing and usage phases of PLM system users' equipment as the main contributors of the PLM system to climate change, acidification, and the depletion of abiotic mineral and metal resources. End-of-life contributes significantly to particulate matter impact, and usage phase, in a nuclear mix country, to ionizing radiation. The policy of purchasing and reselling reconditioned users' equipment is clearly identified as a key lever for reducing the magnitude of these five environmental impacts.

Keywords: product lifecycle management; PLM; environmental life cycle assessment; E-LCA; LCA; ICT; enterprise architecture; sensitivity analysis; case study



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1. Introduction

The desire to integrate information and communication technologies (ICTs) at the very heart of manufacturing systems profoundly defines the contours of the current industrial era. This choice has not only changed the technological landscape of industrial manufacturing but also fostered the creation of new business models focused on digital

innovation and data-driven decision-making [1]. As a result, manufacturing companies are increasingly dependent on the implementation of ICT products and services into their traditional manufacturing processes in order to remain competitive in a globalized and digitized market [2]. No longer isolated, the technical domain is establishing exchanges of product knowledge through sophisticated collaborative platforms [3]. These systems respond to the need to concentrate interdisciplinary expertise for increasingly complex products in compressed development cycles [4].

Product Lifecycle Management (PLM) systems have become the cornerstone of this need for collaboration in the product design domain, providing integrated digital environments where designers, engineers, and production managers work together [5]. The architecture of the PLM system is intrinsically designed according to a three-tier client-server, based on PLM principles that advocate collaboration between experts and data unicity [6], thus requiring the deployment of servers. These platforms facilitate real-time information sharing, version control, and synchronized decision-making across geographically dispersed teams. By enabling seamless collaboration across multiple functions, PLM systems not only accelerate innovation but also embody the new pillar of technological resilience and competitiveness. In the current context of ecological transition in our societies [7], solutions designed to monitor and document each phase of the product life cycle, such as PLM systems, seem particularly well-suited to supporting the design of sustainable products [8].

The functions of the PLM system can be grouped into four main categories. Product data management functions, which were originally the functions of PDM systems, constitute the first category of functions considered [9]. They enable the management of product data throughout its life cycle. Next are engineering functions, which encompass calculation tasks, simulations, and the generation of results related to the products until the end of their life cycle [10]. Another category concerns interface functions: internally, with other digital systems within the manufacturing organization, to enable the transfer or collection of data from ERP, CRM, SCM [11], and LCA systems [12], or even from another PLM system within the organization [13]. Finally, the last major category of functions concerns the orchestration of teams for project management, with, for example, the definition of work packages and responsibilities. By strategically leveraging these functions, organizations can significantly reduce production waste, material inefficiency, and, most importantly, the proliferation of Waste Electrical and Electronic Equipment (WEEE), thereby limiting their environmental impact.

Accurately quantifying these impacts is a considerable challenge that requires the application of a standardized and rigorous methodology: Life Cycle Assessment (LCA) [14,15]. To be successful, comprehensive and consolidated datasets relating to the product must be verified and available. As such, the integration of LCA tools into PLM infrastructures is an urgent challenge. Notable contributions include the work of Yousnadj et al. [16], who successfully interconnected an LCA tool and a PLM system. Similarly, Iancu et al. [17] developed an environmental impact analysis tool integrated into the product design environment, and more recently, Fontana et al. [18] introduced the integration of an LCA tool into a PLM platform. This rapidly changing landscape makes it particularly timely to propose a robust and methodologically refined environmental assessment framework that has been demonstrated to be applicable in demanding industrial contexts [19].

Thus, the current challenge for the industrial sector lies in its need to integrate an ever-expanding volume of data in order to meet the anticipated demands of future societies. It now has the second-fastest-growing data consumption dynamic [20], surpassing the financial services sector and closely following the healthcare sector. This data-intensive trajectory evokes the Jevons paradox, which is increasingly observable in the context of

information and communication technologies [21,22]. Against this backdrop of rapidly escalating digital demand, it is becoming imperative to systematically assess the environmental implications of these technologies. In this regard, the joint report by ADEME and ARCEP [23] reviews the existing framework by identifying two sets of elements that are essential for such assessment: the environmental indicators evaluated and their corresponding methodologies, and the digital equipment and services considered. The positioning of the ADEME–RCP (parent) digital services framework [24] in relation to the ITU standard L.1410 [25] consists of faithfully complying with its guiding principles while enriching them with specific requirements adapted to the context. Furthermore, in order to take into account all the potential impacts of cross-cutting non-digital elements, the approach draws on the ADEME carbon footprint methodology [26], which clarifies the boundaries of Scope 3. However, despite these advances and the progressive momentum surrounding the establishment of analytical frameworks and the assessment of the environmental impacts of digital systems, significant gaps and persistent shortcomings remain. These gaps are mainly exacerbated by the complex definition of the functional unit and the often ambiguous delineation of system boundaries in the IT field [27].

Consequently, it is essential to consider the environmental footprint of digital tools designed to enable the eco-design of manufactured products. This article aims to answer two research questions. What are the hotspots in terms of environmental impact in PLM system architectures throughout their life cycle? How do different PLM system architectures and scenarios influence environmental impact values? We hypothesize that our methodological framework, based on life cycle assessment, allows us to both identify environmental hotspots and propose scenarios to mitigate the environmental impacts of PLM system architecture.

2. Methodological Framework for PLM System LCA

The implementation of an attributional LCA, followed by sensitivity analyses, is an environmental assessment methodology that is difficult to operationalize [28,29]. The objects traditionally studied are hardware, processed materials, software, services, and organizational structures. In order to carry out our PLM life cycle assessment and our sensitivity analysis, the specifications of the PLM system, as an object of study, must be explicitly defined [30]. From the perspective of ISO standard 14040/14044 [14,15], the PLM system, as a strategic process, can be considered as an organization [31], software [9], or a substitute for the hardware it enables to design [10]. The conceptual abstraction inherent in the PLM system generates multiple potential objects of study that can serve as input data for our LCA. To meet the need for digitization of the entire product value chain, a PLM system is offered as a digital service, provided either by the manufacturing organization's internal resources or by its external resources. We considered our PLM system as an IT architecture providing this digital service. Our methodological framework proposal will consist of four interactive parts that will follow the life cycle assessment methodology, as shown in Figure 1.

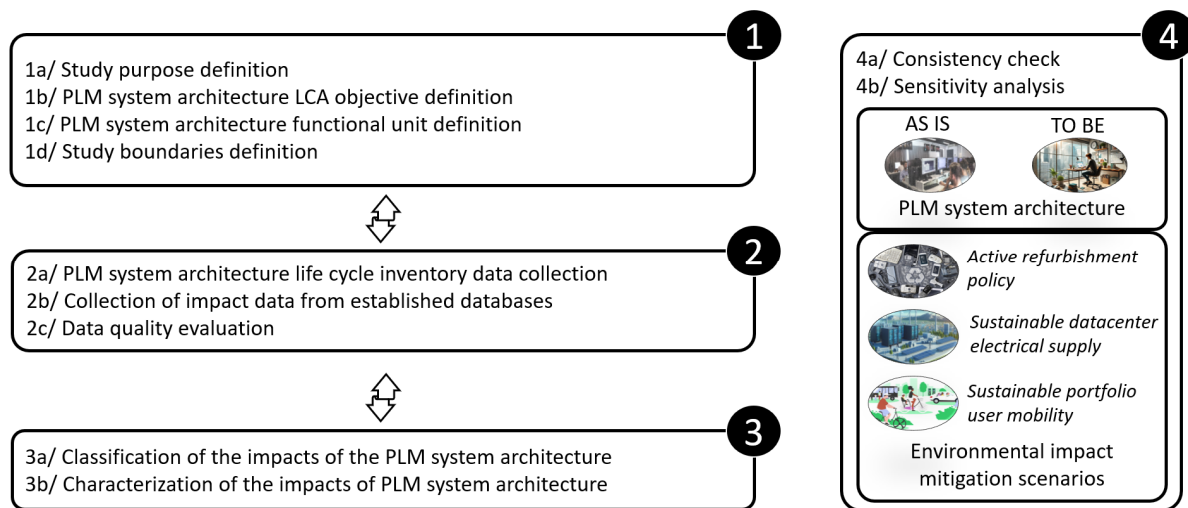


Figure 1. Methodological framework proposal.

2.1. Study Objective, LCA Objective, PLM System Architecture Functional Unit, and Boundaries of the Study

The main objective of this study is to rigorously evaluate various existing and potential PLM system architectures throughout their respective life cycle phases and architectural compositions. The study should provide a robust methodological framework that can be applied after the implementation of the PLM system architecture, labeled AS IS PLM system architecture, in order to enable the systematic evaluation of its environmental footprint. In addition, the study could be extended to the early stages of PLM system architecture design, enabling the systematic assessment and prioritization of potential PLM system architectures, labeled TO BE PLM system architecture, based on their environmental footprint. The target audience includes manufacturing companies seeking to integrate environmental considerations into the design and deployment of their PLM system architecture, while the primary users of the study's findings are IT architects responsible for the strategic implementation and oversight of these systems.

The objective of our life cycle assessment is to compare several life cycles of competing PLM system architectures for the same function unit, with the overall aim of identifying those that are most environmentally friendly. The life cycle phases taken into account include the manufacture of architectural components, their distribution, their operational use, and their end-of-life management. Each of these phases is rigorously assessed according to the five mandatory environmental indicators prescribed for digital services, as defined in the ADOME methodological framework [24]. This assessment ensures both methodological consistency and analytical completeness. These indicators are climate change, acidification, particulate matter, ionizing radiation, and the depletion of abiotic mineral and metal resources. If additional indicators can be assessed, they are included in the assessment as additional results, but are not formally evaluated.

The life cycle assessment is performed using an identical functional unit for all PLM system architectures, thus ensuring a fair, transparent, and scientifically sound basis for comparison. Maintaining a common functional unit is of paramount importance, as it ensures methodological consistency and avoids distortions that could otherwise result from heterogeneous reference frameworks. In the specific context of digital services, the functional unit is measured based on the type of digital functions enabled, connection time, and the number of registered users. Thus, the functional unit to be precisely defined to characterize the PLM system is structured as follows:

«Deploy and guarantee the use of PLM system features for a specified number of registered users during a specified number of connection hours over the course of a year».

Given that PLM system architecture is, by nature, an IT architecture, it is essential to establish boundaries that are appropriate for both the digital services and the technological equipment that comprise it, visible in Figure 2. As highlighted in the state of the art, PLM systems generally feature three-tier IT architectures, comprising user equipment that enables seamless interaction with the PLM data. In addition, network equipment ensures the reliable transmission of PLM data to servers, which meet the critical requirement of data uniqueness essential to the functioning of the PLM system. These servers are either hosted in the organization's datacenters or hosted in the sophisticated infrastructures of cloud service providers. Furthermore, in strict compliance with the recommendations of the methodologies mentioned above, and in particular those that extend the scope 3 of carbon footprint, certain cross-cutting non-digital elements are also systematically taken into account. These include the organizational infrastructures that provide dedicated workplaces for PLM system users, as well as business travel undertaken by these users, both of which contribute indirectly to the overall environmental footprint.

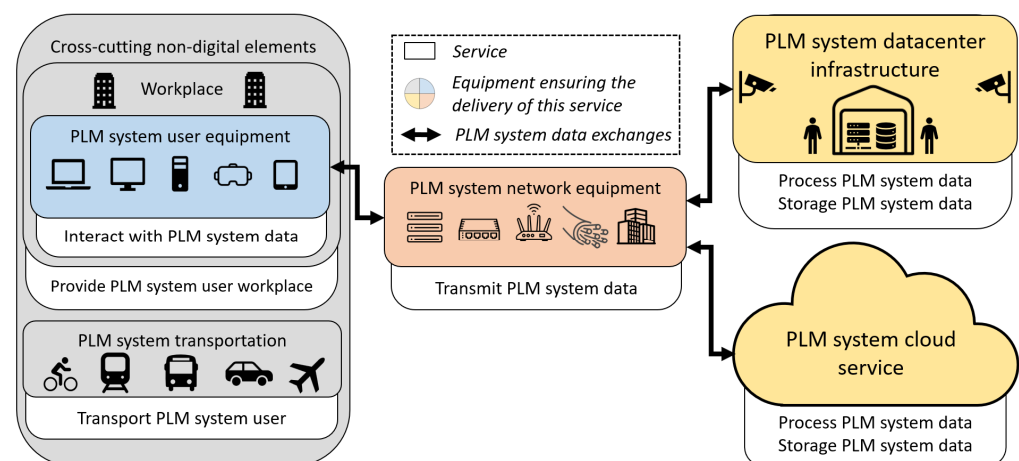


Figure 2. PLM system architecture boundaries considered for LCA methodology.

2.2. Data Collection and Evaluation

2.2.1. Inventory Data Collection Methodology

This phase consists of systematically identifying and quantifying the flow of materials, processes, and energy entering and leaving the various stages of the PLM system architecture's life cycle. Inventory data is collected using a detailed questionnaire completed by the IT solution architect responsible for implementing the PLM system architecture under study. The inventory data used is, therefore, primary data based on the testimony of an expert in the field. In the absence of direct responses, secondary data from generic databases, approximations, or statistical averages are used to complete the questionnaire. The sources and underlying assumptions are meticulously documented and remain fully transparent in the questionnaire. Depending on the architect's responses, new questions are revealed, or certain sections of the questionnaire are closed, reflecting a level of granularity. The first level of granularity focuses on the functional unit of the PLM system architecture, as well as the quantities of equipment and infrastructure needed. The second level deals with the physical and chemical characteristics needed to assess the environmental impact of equipment and infrastructure. Levels three and above refine the responses to the previous levels by relying on physical or chemical parameters distinct from those of level two and provide a more in-depth understanding of the technical characteristics of the various components. An LCA practitioner then retrieves the data entered in the questionnaire by

the IT architect, formulates reasoned assumptions to deal with missing or abnormal values, and finally constructs a coherent inventory dataset.

More specifically, the inventory data required to perform the LCA depends on the types of components included within the PLM system boundaries. For the IT equipment concerned, our inventory data includes the number of items, their lifespan as defined by the organization, their annual energy consumption during use or power requirements, and their weight. For optical fiber, the number is replaced by the total linear length, and the physical dimensions are expressed in linear kilometers. For infrastructure or workplaces related to the manufacturing phase, the data includes the newly constructed floor space, the volume of concrete and mass of steel used, or the weight of materials needed for renovation. For customer-owned infrastructure in particular, the inventory data collected includes location, redundancy level, IT floor space, number of racks, lifespan, installed computing power, server load factor, PUE, type of cooling, number of physical servers, and weight. For cloud service infrastructure, the data collected also includes the type of service provided, service characteristics, service model, service deployment model, size and number of virtual machines, data volume, annual energy consumption, infrastructure location, sustainability practices and policies, and the environmental assessment methodology used to evaluate the activities. For the last element of PLM systems, concerning transport, the data required includes the average daily distance traveled per return journey per PLM system user and the ratio of transport modes. With regard to workplaces, the total floor area, access window in hours by day, lifespan, annual energy consumption during use, or power requirements for air conditioning, heating systems, and spot lighting are requested. The data collected is reported with reference to the previously established functional unit.

Among the inventory data, information is also systematically collected in order to establish allocation keys for multi-purpose equipment. When such equipment is used and mobilized for purposes other than professional tasks related to PLM system activities, whether for other professional functions or for personal use, a proportional allocation of environmental impacts must be considered. This allocation will apply to the impacts associated with the manufacturing, distribution, use, and end-of-life phases. Consequently, it is not the total impact of each phase that is taken into account, but rather a precisely defined and rigorously justified portion, determined on the basis of the data collected through the questionnaire. The data used to construct the allocation keys comes from questions relating to user equipment. For each piece of equipment, the IT architect is asked to indicate whether it is used for other professional activities, such as ERP or CRM tasks, by initially answering YES or NO. A subsequent question then asks for an estimate of the percentage of usage attributable to professional activities on the PLM system. For example, laptops may be used 20% for personal tasks, and 40% for professional tasks related to the PLM system, leaving 8% of their usage entirely dedicated to PLM system operations. Furthermore, it would be incorrect to assume that all user equipment is permanently connected to the connections in question. Therefore, based on the number of connections and weighted by the quantity of devices in each class, a third ratio is introduced. The allocation keys for user equipment are ultimately derived from the product of these three ratios. For network equipment and workplaces, the allocation key is calculated as the average of the allocation keys for the user devices, which provides a more accurate approximation of the proportion of impacts attributable to the PLM system.

2.2.2. Considered Impact Data

Impact data quantifies the impact values of material, process, and energy flows entering and leaving the life cycle phases of the PLM system architecture. These flows specifically concern the manufacturing, distribution, operational use, and end-of-life phases of each

component within the carefully defined scope of the study. Impact data is collected from environmental databases deemed relevant to the object under study. These databases must, on the one hand, be sufficiently general to encompass impact data related to non-electronic and non-electrical elements such as buildings, distribution methods, and transport systems. On the other hand, they must also be specific enough to take into account the electrical and electronic equipment that makes up the PLM system architecture. If this data is missing or incomplete, it becomes necessary to model the components using LCA software, thereby exploiting the impact data extracted from the selected databases. As a general rule, at the end of this phase, a comprehensive table is generated [32], establishing a systematic link between the flows identified during the collection of life cycle inventory data and their corresponding impact data. Table 1 takes the form of a nomenclature, structured in six columns. The first column describes the phase of the PLM system architecture, the second specifies the associated component, the third indicates the flow model type, the fourth details the quantity considered, the fifth lists the corresponding units, and the sixth presents the relevant impact dataset used.

Table 1. Example of the bill of materials at the end of impact data collection for monitor equipment.

Phase	Component	Flow Model Type	Quantity	Units	Impact Dataset Used
Manufacturing	Screen	Material	1600	p	Display, liquid crystal, 17 inches {GLO} market for display, liquid crystal, 17 inches Cut-off, S
	Power cable	Material	2880	m	Cable, connector for computer, without plugs {GLO} market for cable, connector for computer, without plugs Cut-off, S
	Power cable plug	Material	1600	p	Plug, inlet and outlet, for computer cable {GLO} market for plug, inlet and outlet, for computer cable Cut-off, S
Distribution	Aircraft	Process	0	kgkm	Transport, freight, aircraft, unspecified {GLO} market for transport, freight, aircraft, unspecified Cut-off, S
	Container ship	Process	170,537,923	kgkm	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, S
	Train	Process	0	kgkm	Transport, freight train {Europe without Switzerland} market for transport, freight train Cut-off, S
	Lorry	Process	4,000,000	kgkm	Transport, freight, lorry 16–32 metric ton, EURO1 {ZA} market for transport, freight, lorry 16–32 metric ton, EURO1 Cut-off, S

Table 1. Cont.

Phase	Component	Flow Model Type	Quantity	Units	Impact Dataset Used
Usage	France	Energy	13,837	kWh	Electricity, low voltage {FR} market for electricity, low voltage Cut-off, S
	Transport to the collection center	Process	56,975	kgkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified Cut-off, S
	Remanufacturing	Material	0	p	Display, liquid crystal, 17 inches {GLO} market for display, liquid crystal, 17 inches Cut-off, S
	Cable recycling	Process	422	kg	Residue from mechanical treatment, IT accessory {RoW} market for residue from mechanical treatment, IT accessory Cut-off, S
	Screen recycling	Process	422	kg	Residue from mechanical treatment, liquid crystal display {RoW} market for residue from mechanical treatment, liquid crystal display Cut-off, S
End-of-life	Incineration	Process	1266	kg	Hazardous waste, for incineration {Europe without Switzerland} market for hazardous waste, for incineration Cut-off, S
	Landfilling	Process	1266	kg	Average incineration residue {RoW} market for average incineration residue Cut-off, S
	Lorry transport to port	Process	3,275,030	kgkm	Transport, freight, lorry, unspecified {RER} market for transport, freight, lorry, unspecified Cut-off, S
	Container ship transport	Process	48,841,845	kgkm	Transport, freight, sea, container ship {GLO} market for transport, freight, sea, container ship Cut-off, S
	Waste screen	Process	8354	kg	Waste electric and electronic equipment {GLO} market for waste electric and electronic equipment Cut-off, S
	Waste cable	Process	6752	kg	Waste electric and electronic cables {GLO} market for waste electric and electronic equipment Cut-off, S

2.2.3. Data Quality Evaluation

After collecting inventory and impact data, our methodological framework proposal incorporates a data quality assessment, which is a central pillar of the environmental assessment. For each PLM system architecture flow, reliability, completeness, temporal representativeness, geographical correlation, and technological relevance of data are closely examined, as summarized in Table 2. This step not only enhances the transparency and credibility of the assessment but also allows for a clear demarcation between primary data, based on the informed judgment of architecture experts, and secondary data, based on assumptions or extrapolations. Furthermore, it provides essential information on the relative ease or difficulty of modeling the environmental impacts of system components using available software tools and databases. In practice, the absence of specific datasets often requires components to be remodeled, often using judicious substitution data in the form of materials, processes, or energy flows. Such a statement on data quality is indispensable in LCA practice, as it exposes the strengths and limitations of the underlying database, delineates the degree of uncertainty, and ultimately ensures the interpretative robustness of the results. To assess data quality, the PEDIGREE matrix is used to display the scores for data quality criteria, as shown in Table 2.

Table 2. Current pedigree matrix used in ecoinvent 3 [33].

Criterion	Score 1 (Very High)	Score 2	Score 3	Score 4	Score 5 (Very Low)
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market consideration	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<50%) relevant for the market considered, or >50% of sites, but from shorter periods	Representative data from only one site relevant for the market considered or sites, but from shorter period	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal consideration	Less than 3 years of difference from the time period of the dataset	Less than 6 years of difference from the time period of the dataset	Less than 10 years of difference from the time period of the dataset	Less than 15 years of difference from the time period of the dataset	Age of data unknown or more than 15 years of difference from the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area I which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study (ie, identical technology) but from different enterprises	Data from processes and materials under study, but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

2.3. Classification and Characterization of the PLM System Architecture Impacts

The classification phase consists of assigning the flows determined in the second phase to environmental impact categories and translating the inventory flows into impact classes. As stated in our LCA objective, we have considered climate change, acidification, particulate matter, ionizing radiation, and the depletion of abiotic minerals and metal resources as environmental impacts studied for PLM system architecture. The contributions to the impacts of the manufacturing, distribution, active use, and end-of-life phases constituting the PLM system architecture are taken into account in each of these environmental impact categories. At this stage, characterization is carried out at the mid-point level.

The characterization phase is the process by which impacts are rigorously quantified, thereby transforming inventory data into meaningful environmental indicators. Impact characterization is generally carried out using established methodologies and well-documented characterization factors, which enable various inventory flows, such as emissions to air, water, and soil, or energy and material consumption, to be converted into standardized impact indicators. Calculation methodologies that enable the systematic quantification of environmental impacts are selected. By applying these characterization models, each inventory flow is assigned a quantified potential contribution to the relevant impact category, facilitating consistent aggregation of impacts throughout the PLM system architecture life cycle. The choice of characterization method is fundamental, as it determines both the comparability and interpretive validity of the resulting environmental indicators. At this stage, characterization is performed at the end-point level.

2.4. Consistency Check and Sensitivity Analysis

After the characterization phase, the pre-calculated impact data is exported to an Excel file, which also contains the corresponding inventory data. Based on these inventory and impact datasets, and applying the impact calculation formulas detailed in the Appendix A, the impact indicator values are calculated, component by component and life cycle phase by life cycle phase. The results obtained are then represented using carefully structured stacked histograms.

The stacked histogram complies with conventional life cycle assessment standards by illustrating the environmental impact of each life cycle phase considered in the assessment. This representation is particularly useful for highlighting the relative contributions of the PLM system architecture life cycle phases to each impact category in a single diagram. The use of percentage values elegantly mitigates the differences in magnitude between the environmental impact categories studied. Annotations for each of the most contributive phases, those exceeding 10% of the impacts, indicate the respective contributions of the four classes of component classes that make up the PLM system architecture under study, namely user equipment, network equipment, datacenter infrastructure, and cloud services, as well as cross-cutting non-digital elements. This visualization offers a richer perspective than the first, as it allows one to discern the contributions of specific component classes in the environmental impact categories studied and to develop scenarios for mitigating environmental impact. Finally, a sensitivity analysis is performed to compare the impact indicator values of each category selected in the different PLM system architectures studied. This sensitivity analysis includes two histograms per phase: the first shows the contribution values for each phase of the PLM system architecture life cycle, while the second illustrates the contribution values for each component class constituting the AS IS and TO BE PLM system architectures. This type of histogram, which is frequently found in the literature of digital systems [24], provides a clear distribution of impacts between component classes and communicates particularly effectively to IT architects. The technological decisions inherent in these two architectures are made comparable through the application of this sensitivity

analysis, which relies heavily on stacked histograms generated for every impact category studied and gives rise to critical insights and forward-looking architectural propositions.

Subsequently, a second sensitivity analysis is performed, exploring scenarios designed to mitigate the environmental impacts of the AS IS and TO BE architectures. The three scenarios are structured as follows:

- 1: Policy of purchasing and reselling user equipment through reconditioning;
- 2: Datacenter infrastructure relocation to a space using a sustainable electricity mix;
- 3: Transport of PLM system users using a portfolio of sustainable mobility.

A sensitivity analysis is then performed using stacked histograms, generated for each impact category and each scenario applied to the PLM system AS IS and TO BE architectures. This representation allows for a nuanced comparison of the deployment of strategic levers for environmental impact mitigation, based on the specificities of the architectures examined.

3. Use-Case Results

3.1. AS IS and TO BE PLM System Architectures

Arts et Métiers Institute of Technology uses a PLM system to train its students in product design. Currently, the IT architecture of this PLM system is limited to on-site use at the institution's premises, with the exception of professors, who are authorized to work remotely one day per week. A future architecture is being considered that would allow remote use of the PLM system for remote working. In this architecture, students would access the school network via the public internet and use the PLM system remotely. We applied the methodological framework proposal described in the previous section to the current and future architecture of Arts et Métiers Institute of Technology's PLM system.

The ultimate goal of our study is to elucidate the origins of the environmental impacts associated with these two architectures and to provide reasoned information that can guide the preference for one or the other architecture—not only in terms of technological choices but also with regard to scenarios for reducing environmental impact. Consequently, the objective of our life cycle assessment is to establish a comparative assessment of the environmental impacts associated with these two architectures, encompassing their entire life cycle and component structure, within the analytical framework of selected environmental impact categories.

More specifically, the AS IS and TO BE PLM system architecture of Arts et Métiers Institute of Technology is used 170 days per year, for 1200 associated connections, with an average of 4 h per connection. This leads to the following functional unit:

«To deploy and ensure the use of (1) core product data management functions, (2) engineering functions, and (3) orchestration function for 3050 declared users during 816 000 connection hours over the course of a year».

The limits of the Arts et Métiers Institute of Technology PLM system architecture include the following:

- User equipment: the manufacturing, distribution, use and end-of-life phases are taken into account for laptops with chargers, HDMI cables and mice (T1); desktop computers with central processing units, power cables, HDMI cables, mice and keyboards (T2); monitors with screens and power cables (T3); tablets with chargers (T4); and virtual reality headsets (T5).
- Network equipment: the manufacturing, distribution, use, and end-of-life phases are taken into account for fixed network equipment such as DNS servers (R1), routers (R2), switches (R3), optical fiber (R4), and physical network buildings (R5).

- Datacenter infrastructure: the manufacture, distribution, and use of the datacenter infrastructure building with its associated technical environments (D1) and its IT equipment (D2) belonging to the school for the processing of PLM-related data. Cloud services, which are storage services (D3), are also taken into account in the usage phase.
- Non-digital cross-cutting elements: Manufacture, distribution, and use of CAD computer rooms located on the sites of the Arts et Métiers Institute of Technology (Tr1). The use of transport modes by students and professors, in accordance with the remote working policy, is also included within the limits of the system (Tr2).

Table 3 shows the lifespan, weight, power nameplate, quantity, and duration of use needed to perform the life cycle assessment of the IT equipment included in the AS IS and TO BE Arts et Métiers PLM system architecture.

Table 3. Inventory data for IT equipment in AS IS and TO BE PLM system architectures.

IT Material	Lifespan (Years)	Weight (kg)	Power Nameplate (kW)	AS IS Quantity (ø) and Usage Time (h/Year)	TO BE Quantity (ø) and Usage Time (h/Year)
T1: Laptop	5	3.15	0.127	100–816,000	100–816,000
T1: Laptop charger	5	0.34		100–816,000	100–816,000
T2: Central units	6	11.30	0.530	800–816,000	800–816,000
T2: Cable HDMI	6	0.28		900–816,000	900–816,000
T2: Mouse	6	0.12		800–816,000	800–816,000
T2: Keyboard	6	1.18		800–816,000	800–816,000
T3: Screen	7	5.10	0.026	1600–816,000	800–816,000
T2 and T3: Power cable	7	0.18		2400–816,000	1600–816,000
T4: Tablet	3	0.60	0.020	10–816,000	0–0
T4: Tablet charger	3	0.06		10–816,000	0–0
T5: VR headset	5	1.30	0.018	10–816,000	0–0
R1: DNS server	4	7.80	0.2	5–1836	5–8766
R2: Router	6	2.59	0.004	10–1836	10–8766
R3: Switch	5	7.11	0.112	50–1836	50–8766
R4: Optical fiber (1 m)	20	0.01095	0.00006	130,000 m–1836	130,000 m–8766
D2: Datacenter servers	5	7.8		2–1836 (2.45 kW)	2–8766 (1 kW)

For the AS IS and TO BE architecture, user equipment allows for 1200 daily connections related to PLM, non-PLM work tasks, and personal activities. Two of the three allocation ratios are determined based on responses from the IT solution architect in Table 4. The third is determined by the number of connected equipment. For example, of the 1200 daily connections, laptops account for 100 of the 920 potential connected equipment. Their contribution is therefore estimated at around 130 connections per day. The network equipment and workplace of the PLM system are not exclusively dedicated to PLM-related functions, but also to the activities of the Arts et Métiers Institute of Technology. They also have an allocation ratio modeled by the average of the allocation ratios of the user equipment.

Table 4. Allocation keys to the AS IS and TO BE PLM system architecture.

Components	AS IS Allocation Key ($C_{day,eq}-C_{pro,eq}-C_{pers,eq}$)	TO BE Allocation Key ($C_{day,eq}-C_{pro,eq}-C_{pers,eq}$)
T1: Laptops	0.11–0.4–0.8	0.11–0.4–0.8
T2: Central units	0.87–0.75–1	0.89–0.4–0.8
T3: Screens	0.87–0.75–1	0.89–0.4–0.8
T4: Tablets	0.01–0.3–0.8	x
T5: VR headsets	0.01–1–1	x
R1: DNS Server	0.27	0.20
R2: Router	0.27	0.20
R3: Switch	0.27	0.20
R4: Optical fiber	0.27	0.20
R5: Network building	0.27	0.20
Tr1: Workplace	0.27	x

Several buildings are included within the defined perimeter of the PLM system. Their respective inventory data are detailed in Table 5. Part of the datacenter building and energy supply at the Arts et Métiers Institute of Technology is allocated to PLM system activities. Currently, all operations cover a total of 200 m², including 50 m² of IT space and 10 racks with an IT power demand of 35 kW. Only one rack housing two servers is used for PLM system activities, which corresponds to 20 m² of the building's total surface area and an IT power demand of 3.5 kW. The TO BE architecture proposes a reduction in the building's total surface area to 10 m² dedicated to PLM system activities and an IT power demand of 2.5 kW. In addition, server load factor, which represents the ratio between energy currently supplied and the maximum possible over a given period, decreases from 70% to 40%, due to the distribution of the connection load, which is limited to the school's opening hours for the AS IS architecture, but extended continuously over a 24 h cycle for the TO BE architecture. The Power Usage Effectiveness of the datacenter, a quotient that systematically exceeds unity, representing the ratio between the total energy consumed by the datacenter and the energy spent on cooling the IT equipment, could not be obtained, and an average PUE of 1.57 was adopted instead [34]. However, the environmental impacts associated with the manufacture, distribution, and end-of-life of the technical datacenter environment are not taken into account due to the lack of available primary data. The building's lifespan has been set at 40 years, and its weight is 20 tons per m². These PLM system architectures rely on a cloud service provider for data storage during the use phase. The total volume of data stored during the one-year assessment period is 970 GB for both the AS IS and TO BE architectures.

The buildings of the Arts et Métiers Institute of Technology were constructed in the 19th and 20th centuries. The CAD rooms have undergone renovations, with an average lifespan of 40 years and a total mass of renovation materials estimated at 1359 kg per CAD room. Each of these 32 rooms covers an area of 30 m² and is supplied with electricity for lighting, heating, and air conditioning, requiring an average power of 1.425 kW throughout the year. The rooms are used for an average of 10.8 h per day, which corresponds to the standard daily opening hours of the sites.

Table 5. Inventory data for buildings in AS IS and TO BE PLM system architectures.

Buildings	Lifespan (Years)	AS IS Quantity (ϕ), Surface (m^2), Weight (kg), Power (kW), and Usage (h/Year)	TO BE Quantity (ϕ), Surface (m^2), Weight (kg), Power (kW), and Usage (h/Year)
R5: Network	40	1–x–25,000–x–x	1–x–25,000–x–x
D1: Datacenter	40	1–20–20,000–1.400–1836	1–10–10,000–0.570–8766
Tr1: Workplace	40	32–30–1359–1.425–1836	0–0–0–0–0

The last building included in the inventory data is the facility that houses the school's network equipment. It is a modest structure whose sole function is to house the institution's network systems. In our study, only the impacts related to concrete and steel are taken into account.

The transport processes taken into account are specified in Table 6. The distribution of user equipment, network equipment, and servers is modeled using the same approach as in the ADEME report [23], assuming an average transport distance by lorry freight of 500 km between Paris and the Arts et Métiers sites. The distribution of materials needed to build the network housing, datacenter, and workplaces is also taken into account. An average transport distance by lorry freight of 100 km between the construction companies' sites and those of the Arts et Métiers is added.

Table 6. Transport inventory data of AS IS and TO BE PLM system architectures.

Transport	Life Cycle Phase Concerned	Architecture Concerned	Distance (kms)	Modality
Pekin › Paris	Distribution	AS IS–TO BE	8330	Aircraft
Pekin › Paris	Distribution	AS IS–TO BE	20,204	Container ship
Pekin › Paris	Distribution	AS IS–TO BE	11,661	Train
Paris › Workplace	Distribution	AS IS–TO BE	500	Lorry freight
Construction company › Workplaces	Distribution	AS IS	100	Lorry freight
User home › Workplaces	Usage	AS IS	1.8	Small petrol car
Workplaces › Local collection centers	End-of-life	AS IS–TO BE	6.75	Lorry freight
Local collection centers › Le Havre port	End-of-life	AS IS–TO BE	485	Lorry freight
Le Havre port › Agbogbloshie port	End-of-life	AS IS–TO BE	7233	Container ship

The total number of commutes made by all users is calculated by dividing the average annual total connection time by the time slot during which the dedicated rooms are accessible. Adjustment factors reflecting remote working policies and the allocation keys of PLM-related professional tasks carried out in these rooms were also included, as shown in Formulas (A3) and (A17) in the Appendix A. We then assumed that the average distance travelled by users to get to and leave workplaces was 1.8 km, using only small petrol cars.

The end-of-life phase of the Arts et Métiers AS IS and TO BE PLM system architectures involves transporting IT equipment by lorry freight an average of 6.75 km to the nearest waste collection center, followed by three possible disposal routes, with a ratio of [35]:

- Local recycling, with a recycling rate of 0.05;
- Incineration followed by landfill, with a rate of 0.15;

- Transportation by lorry freight via the port of Le Havre and re-export by ship to an electronic waste landfill site, Agbogbloshie, located in Ghana, as a representative example. The re-export rate taken into account is considered to be 0.8.

Once the inventory data for the two architectures under consideration has been fully specified, we proceed to collect the corresponding impact data. To this end, we use exclusively the ecoinvent 3.9.1 database, with the sole exception of data relating to data storage, for which the negaoctet 01.05.000 database is used. Although ecoinvent 3.9.1 is widely recognized as a generic database and provides impact data for several IT components detailed in the inventory, it is not entirely specific to digital equipment and services. As a result, certain specific components, including virtual reality headsets, servers, switches, and optical fiber, require careful remodeling. To this end, Simapro 9.6.1 LCA software is used. The choices and assumptions underlying this remodeling are documented in a Supplementary File, which serves as a comprehensive bill of materials and summarizes the data collection phase preceding the impact assessment.

Five impact categories are considered in the classification phase:

- climate change;
- acidification, ecosystem end-point;
- particulate matter, human health end-point;
- ionizing radiation, human health end-point;
- depletion of abiotic resources, minerals and metals, resources end-point.

The assessment of the quality of LCA data for both AS IS and TO BE PLM system architectures is carried out using the PEDIGREE matrix presented in Section 2.2.3. This representation is then summarized in Table 7, where the columns correspond to the scores of the criteria observed, while the rows delimit the flows of PLM system architectures.

Table 7. Data quality dimension analyses of studied PLM system architectures flows.

Flows\Criterion	Reliability	Completeness	Temporal Consideration	Geographical Correlation	Further Technological Correlation
T1: Laptops	4	4	4	2	3
T2: Central units	4	4	4	2	3
T3: Screens	4	4	4	2	3
T4: Tablets	4	4	3	2	3
T5: VR headsets	4	4	4	2	3
R1: DNS Server	4	4	4	2	4
R2: Router	4	4	4	2	3
R3: Switch	4	4	5	2	4
R4: Optical fiber	4	4	4	2	4
R5: Network building	4	4	4	2	4
D1: Datacenter building	4	3	4	2	2
D2: Datacenter IT equipment	4	3	4	2	4
D3: Cloud storage	4	3	3	2	2
Tr1: Workplace	4	4	4	2	4
Tr2: User transportation	4	5	4	2	2

In terms of reliability, all flows received a uniform score of 4 thanks to the testimony of the specialized PLM system architect. With regard to completeness, user and network equipment in workplaces were determined from empirical observations at a single campus and extrapolated to the other eight campuses, resulting in a score of 4. Datacenter operators provided partial but verified information on building infrastructure, number of servers, and storage volume, which justified a completeness score of 3. Conversely, user transport flows were based on very rough assumptions, with the lowest score of 5.

In terms of temporal representativeness, most datasets came from ecoinvent 3.9.1 and dated from 2011, remaining valid until 2022, which justified a score of 4. Two more recent datasets, concerning tablets and cloud storage, covered a period of 6 to 10 years, while the switches were modeled using an obsolete dataset, resulting in a score of 5. With regard to geographical correlation, data is available at the national level, in particular to capture the specificities of European electricity mixes, which corresponds to a score of 2. Finally, technological correlation scores ranged from 2 to 4: cloud services, datacenter building, and user transport were based on analogous flows or comparable companies, while user equipment and routers were modeled using comprehensive ecoinvent 3.9.1 datasets, but with potentially divergent technologies. In contrast, servers, switches, optical fiber, network buildings, datacenter IT equipment, and workplaces are modeled using proxy assembled datasets, reflecting the composite and hybrid nature of these flows.

All impact data comes from the ecoinvent 3.9.1 database. For cloud data storage, missing impact data is replaced with data from negaoctet 01.05.000. The model is based on the functional unit: «cloud storage of 1 GB of data over one year via a fixed connection in France» and excludes user equipment. Impacts related to datacenter infrastructure and its associated network are taken into account and parameterized based on Netflix's technical storage performance, with a PUE of 1.3. The lifespan of firewalls, switches, routers, servers, and storage equipment is 5 years, while that of support equipment and architecture is 25 years. Thus, replication, backups, and redundancy classes are not taken into account in the dataset [36].

In order to integrate additional impact data sources, it is essential to ensure that they are based on consistent methodologies for classifying and characterizing environmental impact. Consequently, this common calculation methodology is the Environmental Footprint 3.1 (EF 3.1) [32], presented in the Appendix B. EF 3.1 was developed by the European Commission to harmonize the environmental assessment of products (PEF) and organizations (OEF). The Environmental Footprint 3.1 calculation methodology was chosen because of its unified normative framework designed to standardize life cycle assessments across Europe, ensuring both comparability and methodological consistency of impact results [37]. The results for the 11 other impact categories will be published in the Supplementary File but will not be included in the final analyses.

The five impact categories identified during the classification phase encompass all the final areas requiring protection: climate change; ecosystem integrity through acidification; human health in relation to fine particulate matter and ionizing radiation; and the conservation of abiotic mineral and metallic resources.

The pre-calculated impact data is exported to an Excel file where the environmental indicator values are calculated. The calculation combines the impact data established during characterization and the inventory data collected from the architect specializing in our PLM system. The formulas used are presented in the Appendix A. Once the calculations have been performed for the four phases of the PLM system life cycle, the resulting LCAs for the AS IS and TO BE architectures are generated and displayed in Figures 3 and 4 below.

As illustrated in Figure 4, the magnitude of the contributions of the life cycle phases of the AS IS and TO BE PLM system architectures varies depending on the environmental

impact categories considered, but their relative weight remains similar in both architectures. The manufacturing phase appears to be the main contributor to climate change, ecosystem acidification, and the depletion of abiotic mineral and metallic resources, accounting for 67%, 73%, and 89%, respectively, for the AS IS architecture, and 64%, 67%, and 88% for the TO BE architecture. However, the use phase is largely dominant in the category of ionizing radiation, with a contribution of over 95% and 97%, mainly due to the specific nature of the French electricity mix, which is composed of approximately 70% nuclear energy [38]. On the other hand, the end-of-life phase contributes 75% and 88% to fine particle emissions on the African continent, with two-thirds for AS IS architecture and four-fifths for TO BE architecture, coming from the 130 km of optical fiber modeled as 1.4235 tons of electrical and electronic cable waste. In the ecoinvent 3.9.1 database, the impact value of the particles associated with 1 kg of this waste is $1.62 \cdot 10^{-5}$ disease occurrence, which is four orders of magnitude greater than that of waste electrical and electronic equipment.

Given these key contributing phases, which are intrinsically linked to the components of the PLM system architecture, it is already possible to mitigate the impact of user equipment manufacturing, regardless of the architecture adopted. A widely recognized strategy in the literature is to extend the lifespan of the IT equipment. To this end, an initial scenario has been modeled, in which the Arts & Métiers Institute of Technology actively implements a policy of purchasing, reselling, and reusing user equipment in collaboration with reconditioning entities. Such an approach should mitigate impacts in three key categories, namely climate change, acidification, and the depletion of abiotic mineral and metal resources. Furthermore, given the significant contribution of the usage phase to the impacts of ionizing radiation, a scenario in which the electricity powering both user equipment and servers comes from renewable rather than nuclear energy is also considered. At present, however, only the scenario involving the supply of renewable electricity to the datacenter infrastructure has been selected, thus constituting our second scenario. A third scenario is also being developed, aimed at reducing the impacts of fine particle emissions associated with the end of life of electrical and electronic cables, particularly optical fiber, in digital landfills, as illustrated in Figure 3.



Figure 3. A set of illustrations taken from [39,40] illustrating the end-of-life scenario for electrical and electronic cables waste after its re-export to Agbogbloshie, Ghana.

As illustrated in Figure 5, conversely, the secondary contributor to climate change, ecosystem acidification and depletion of abiotic minerals and metal resources, namely the usage phase, is always similar, representing 32%, 25%, and 8%, respectively, for the AS IS architecture, and 32%, 29%, and 10% for the TO BE architecture. Within these usage phases, it is mainly user equipment and cross-cutting non-digital elements, in particular user mobility in small petrol cars, which account for 35% of the usage phase impacts on climate change and acidification. Consequently, one possible scenario would be to offer PLM system users a portfolio of sustainable mobility solutions, thereby mitigating these harmful impacts.

This heterogeneous distribution of the main contributions in the two PLM system architectures highlights the profound capacity of information and communication technology systems to have very different impacts on the environment, depending on the specific phase of their life cycle.

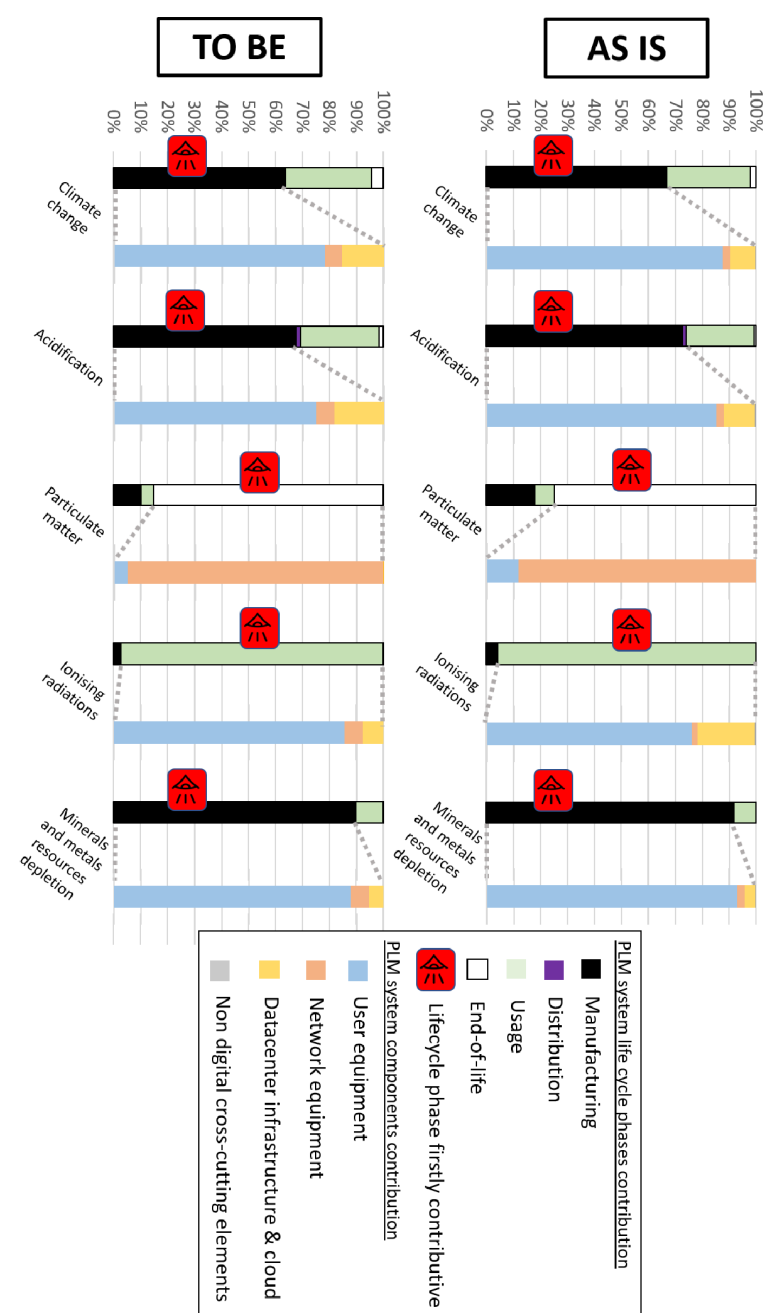


Figure 4. LCA results with the top contributor of AS IS and TO BE PLM system architectures.

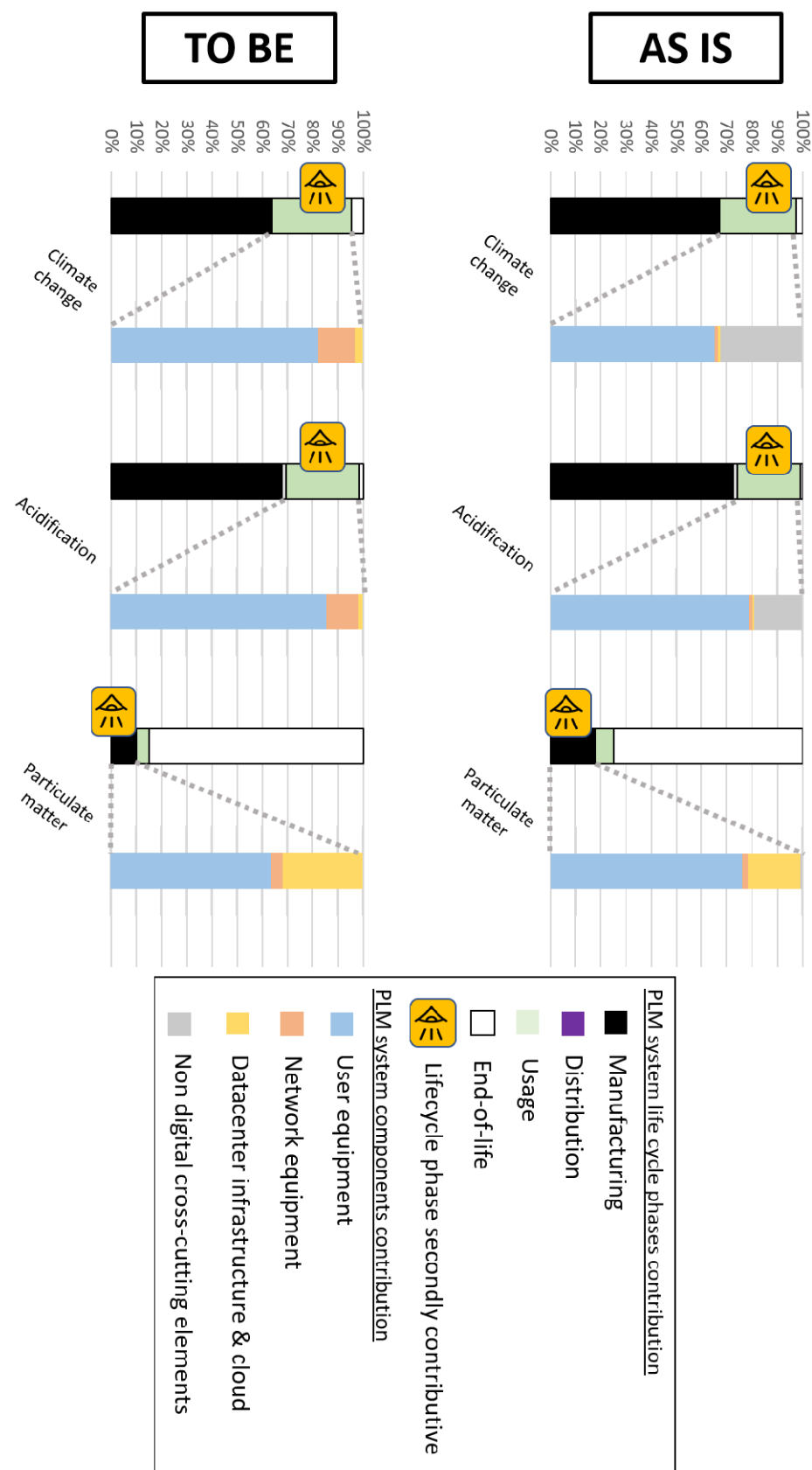


Figure 5. LCA results with the second contributor of AS IS and TO BE PLM system architectures.

In terms of indicative values, we then compare our impacts using sensitivity analysis, as elegantly illustrated in Figure 6.

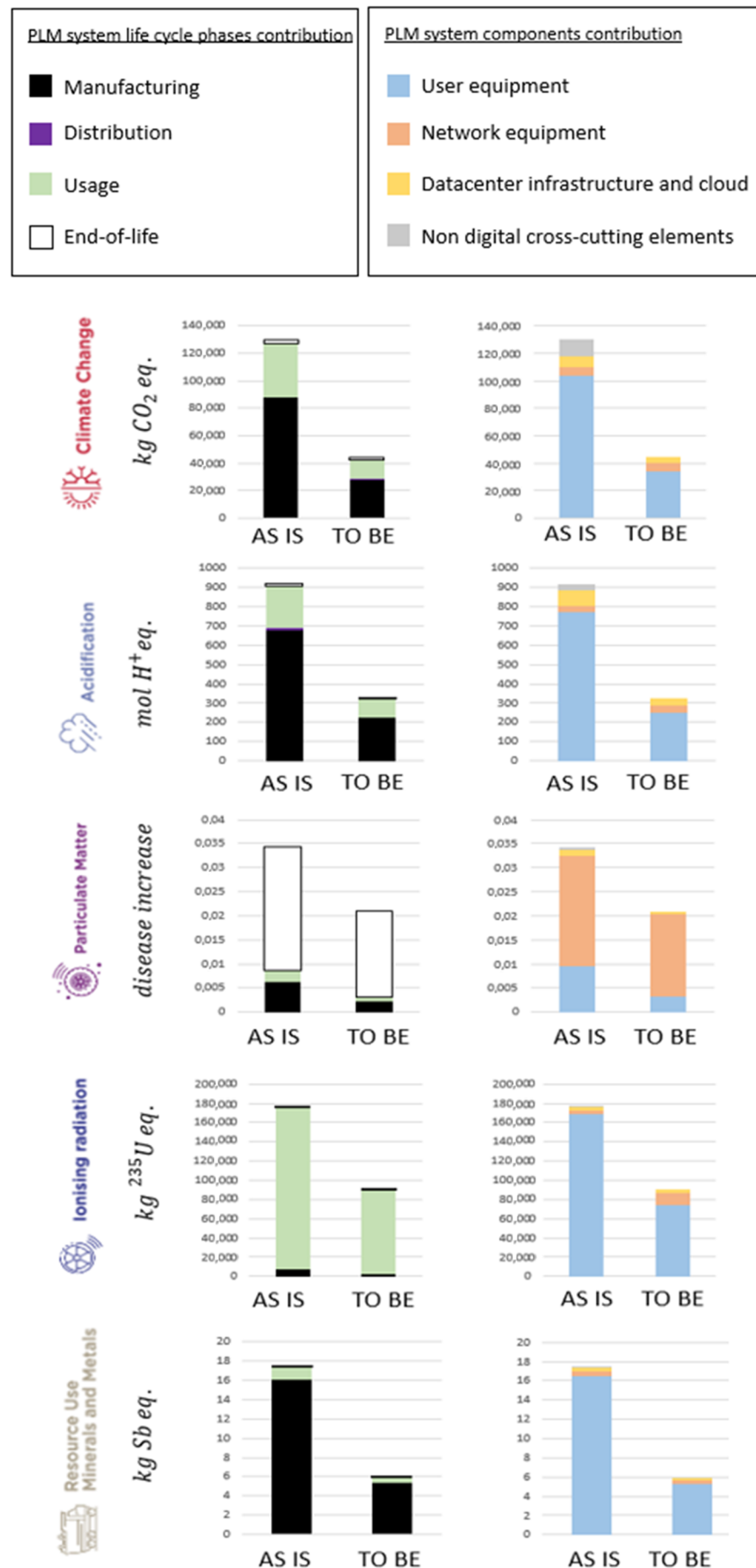


Figure 6. Sensitive analysis results of AS IS and TO BE PLM system architectures.

As illustrated in Figure 6, the modeled TO BE architecture has significantly lower impact values than the current AS IS architecture of the PLM system. Respectively, these impacts decreased by 66%, 64%, 39%, 49%, and 66% across the environmental impact categories, including climate change and beyond. The predominance of user equipment contributions is particularly striking in almost all categories, with the notable exception of fine particulate matter, where network equipment, particularly optical fiber, appears to be the main contributor. In the TO BE architecture, network equipment ranks second in terms of contributor, surpassing datacenter infrastructure and cloud services, which are less heavily used. Overall, the TO BE architecture, which envisions a remotely accessible PLM system for students, has a significantly lower environmental impact than the initial AS IS architecture.

3.2. Environmental Impact Mitigation Scenarios

Our analyses of the life cycle of the two PLM system architectures enabled us to identify the most contributory life cycle phases among the five impact categories studied. These phases are similar and independent of the architectural alternatives considered. Within these life cycle phases, the contributions of each class constituting the PLM system architecture are examined. Based on these analyses, impact reduction scenarios have been formulated and are discussed below in this section.

The same functional unit, system boundaries, inventory, classification, and characterization of environmental impact as previously defined for the study are used. Only a limited set of the following parameters, depending on the scenario considered, is used to determine the environmental impact results of the PLM system architectures using formulas:

Scenario 1, in which for each category of PLM system user equipment:

- 50% is purchased as reconditioned equipment, with an upstream lifespan of 3 years;
- 50% is sold to reconditioning organizations with a 2/3 probability of repair and a downstream lifespan of 3 years;
- 33% are reused with a downstream lifespan of 2 years.

Scenario 2:

- The datacenter infrastructure that supports the PLM system architecture is transferred to Norway.

Scenario 3, in which user mobility is ensured through a combination of sustainable modes of transport:

- The total distance traveled by all users is divided equally between the following five modes of transport: train, bus, tram, bicycle, and electric bicycle.

These three scenarios are applied to the AS IS and TO BE PLM system architectures of the Arts et Métiers Institute of Technology. Only the third scenario cannot be deployed on the TO BE architecture, as no impact is attributed to the PLM system in terms of user transport. The results of applying these three scenarios are presented in the form of a sensitivity analysis in Figure 7, then detailed in Figures 8 and 9. This non-attribution is illustrated in Figures 8 and 9 by the addition of grey boxes. The results in Figure 7 reveal that the three scenarios invariably lead to a reduction in the environmental impacts of the architectures. The contributions of PLM system architectures to environmental impacts, life cycle phases, and PLM system architecture components are illustrated in Figures 6 and 7, then analyzed to elucidate the influence of the scenario.

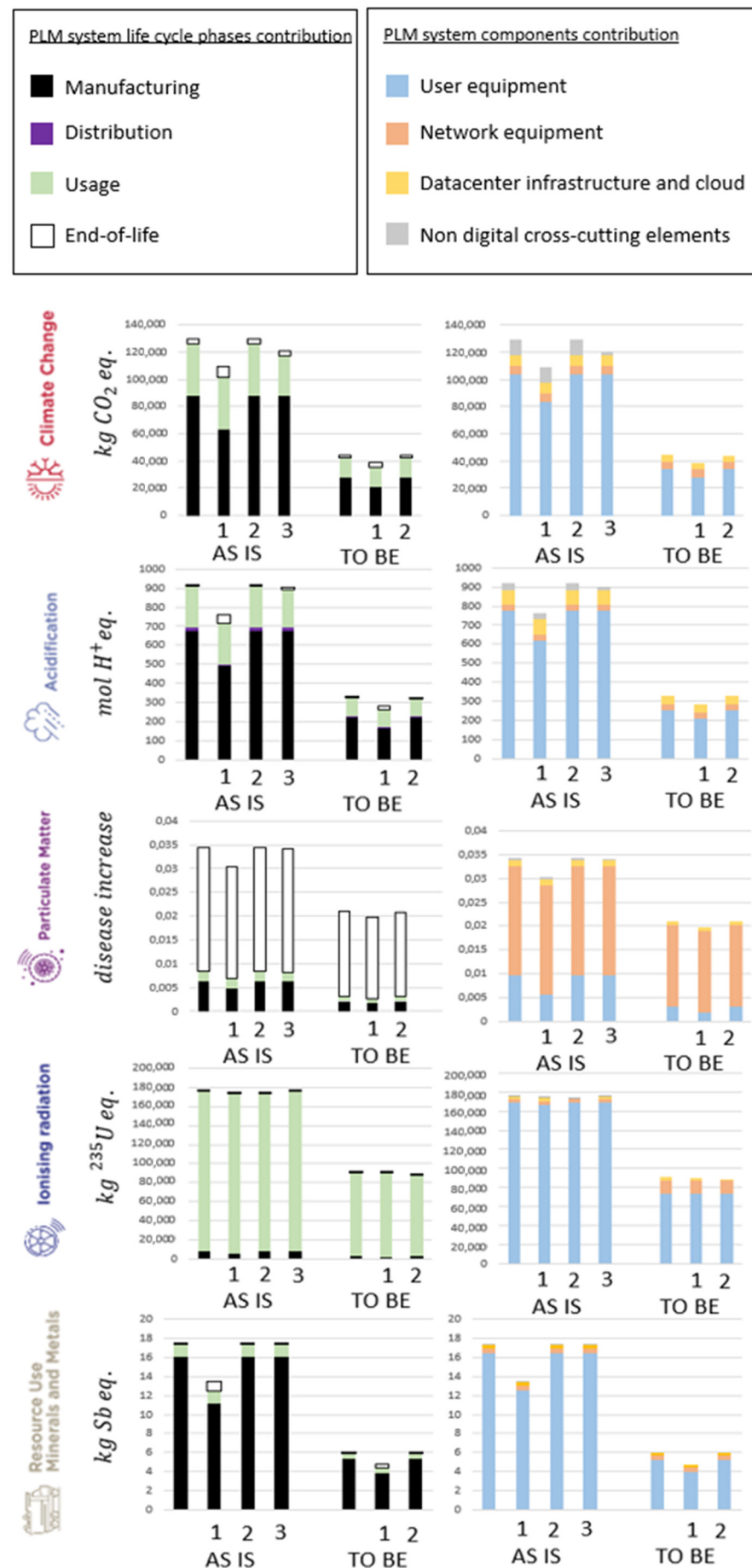


Figure 7. Sensitive analysis results of AS IS and TO BE PLM system architectures across scenarios.

		Fabrication		Distribution		Usage		Fin de vie	
		AS IS	TO BE	AS IS	TO BE	AS IS	TO BE	AS IS	TO BE
 Climate Change	Scenario 1	↘ 28 %	↘ 26 %	↘ 58 %	↘ 52 %			↗ x 2.6	↗ x 1.7
	Scenario 2					↘ 1 %	↘ 2 %		
	Scenario 3					↘ 23 %			
 Acidification	Scenario 1	↘ 27 %	↘ 27 %	↘ 60 %	↘ 54 %			↗ x 2.9	↗ x 5.4
	Scenario 2					↘ 1 %	↘ 2 %		
	Scenario 3					↘ 7 %			
 Particulate Matter	Scenario 1	↘ 24 %	↘ 19 %	↘ 59 %	↘ 53 %			↘ 9 %	↘ 4 %
	Scenario 2								
	Scenario 3					↘ 9 %			
 Ionising radiation	Scenario 1	↘ 30 %	↘ 28 %	↘ 56 %	↘ 50 %			↗ x 23.5	↗ x 11.2
	Scenario 2					↘ 1 %	↘ 3 %		
	Scenario 3								
 Resource Use: Minerals and Metals	Scenario 1	↘ 31 %	↘ 29 %	↘ 55 %	↘ 50 %			↗ x 489	↗ x 225
	Scenario 2								
	Scenario 3					↘ 7 %			

Figure 8. Evolution of PLM system architectures life cycle phase contributions across scenarios.

		User equipment		Network		Datacenter & cloud		Non-digital	
		AS IS	TO BE	AS IS	TO BE	AS IS	TO BE	AS IS	TO BE
 Climate Change	Scenario 1	↘ 20 %	↘ 18 %						
	Scenario 2					↘ 3 %	↘ 6 %		
	Scenario 3							↘ 77 %	
 Acidification	Scenario 1	↘ 20 %	↘ 18 %						
	Scenario 2					↘ 1 %	↘ 3 %		
	Scenario 3							↘ 46 %	
 Particulate Matter	Scenario 1	↘ 40 %	↘ 39 %						
	Scenario 2								
	Scenario 3							↘ 60 %	
 Ionising radiation	Scenario 1	↘ 1 %	↘ 1 %						
	Scenario 2					↘ 80 %	↘ 84 %		
	Scenario 3							↘ 10 %	
 Resource Use: Minerals and Metals	Scenario 1	↘ 24 %	↘ 24 %						
	Scenario 2								
	Scenario 3							↘ 83 %	

Figure 9. Evolution of PLM system architecture components contributions across scenarios.

The phases of the life cycle of AS IS and TO BE PLM system architectures have a similar impact on the environment in all three scenarios. There are variations in the magnitude of these impacts during the different phases of their life cycle. Scenario 1 reduces the impacts associated with the manufacture of the PLM system architectures, but simultaneously increases those associated with end-of-life, except in the case of fine particles, for which impacts are systematically reduced in both phases. This increase is particularly significant in the impact categories of ionizing radiation and the depletion of abiotic mineral and metallic resources. This increase can be explained by the need to extract new resources for repair processes and by France's dependence on nuclear electricity to carry out these renovations. Another notable result highlighted by Scenario 1 is the significant reduction in distribution-related impacts. Indeed, the longer lifespan of user equipment not only influences the manufacturing phase but also the distribution phase of IT equipment, which consequently becomes less frequent and less restrictive.

Scenario 2 results in only a modest reduction in the impacts of the PLM system architecture's use phase on climate change, acidification, and ionizing radiation. This slight decrease is attributable to the specific nature of our case study, which is limited to an academic context with two servers in operation. In an industrial PLM system architecture requiring a larger number of servers and a significantly higher volume of stored data, the environmental impacts associated with the use phase could become significantly greater, and the reductions achieved in the second scenario would be all the more pronounced. Furthermore, in Scenario 2, the use phase does not appear to have any influence on the impact categories related to fine particulate matter or depletion of abiotic minerals and metal resources.

Finally, Scenario 3 significantly reduces the impacts of the PLM system architectures use phase. This reduction is particularly marked for climate change, as the absence of petrol car journeys reduces the impacts generated by cross-cutting non-digital components.

The components of the AS IS and TO BE PLM system architectures contribute similarly to the environmental impacts in all three scenarios. Each scenario allows a particular category of PLM system components to see its relative contribution decrease. Scenario 1 reduces the impacts associated with user equipment, with a particularly pronounced decrease in the categories of particulate matter, depletion of abiotic minerals and metal resources, climate change, and acidification. On the other hand, its effect on the impacts of ionizing radiation is only marginal. This is because Scenario 1 mainly aims to mitigate impacts upstream and downstream of the usage phase, and therefore does not extend to the use phase itself, which remains the main contributor to ionizing radiation.

Scenario 2 focuses its impact reductions on the datacenter infrastructure and cloud services. As noted earlier, the inherent limitations of our use case allow us to observe only modest decreases in the climate change and acidification impacts of infrastructure and cloud services. However, Scenario 2 does not appear to mitigate the impacts of datacenter infrastructure and cloud services in terms of fine particulate matter or mineral and metallic resources depletion, as the main phases contributing to these categories occur upstream and downstream of the use phase targeted by this scenario. Nevertheless, there is a marked decrease in the impacts of datacenter infrastructure and cloud services in the category of ionizing radiation. This reduction is due to Norway's energy mix, which is composed of more than 95% renewable energy, compared to 30% in France in 2024 [38].

Finally, Scenario 3 leads to a substantial reduction in contributions linked to user travel, which are cross-cutting non-digital elements and concern all the impact categories taken into account in the AS IS architecture. This decrease is slightly less pronounced in the ionizing radiation impact category, a result that stems from the modeling of mobility

types. As combustion engine vehicles are powered by petrol, their absence does not reduce impacts as significantly as would be the case with electrified mobility in France.

4. Discussion

4.1. Contributions

4.1.1. Holistic Life Cycle Modeling of PLM Systems

In this research, the application of LCA methodology to an abstract and intangible system, the PLM system, is critically questioned. To do this, the methodological steps prescribed in the LCA standard were followed, while conceptualizing our PLM system as a service. Customized tools, designed for PLM systems architectures but widely adaptable to digital services, were developed and used to collect inventory data and calculate impacts using pre-characterized impact results. The strength of these tools lies in their holistic consideration of all life cycle phases and their ability to encompass the entire boundaries of the PLM system.

4.1.2. Formulas Proposal for Impact Evaluation

The explicit formulation of the equations proposed for calculating environmental impacts is a valuable contribution to the reproducibility of the experiment, the methodological framework, and potentially other LCAs of digital systems. With remote working becoming increasingly commonplace in manufacturing organizations, these formulas, based on ratio-based approaches, could be reused and refined.

4.1.3. Comparison of Current and Future PLM System Architecture (AS IS vs. TO BE)

Comparing two potential PLM system architectures enables the integration of a decision-making process aimed at mitigating the environmental impact of the PLM system case study. Consequently, these results help decision-makers evaluate the range of existing PLM architectures and assess their respective environmental impacts. This approach provides both actionable insights and strategic resources for planning and implementing measures to reduce long-term environmental impact.

4.1.4. Scenarios-Based Approach for Impact Reduction

The formulation of three scenarios based on PLM system architectures enables decision-makers to identify exploitable levers and assess the potential trade-offs associated with implementing such strategies. Even when a manufacturing company cannot modify its PLM system architecture due to security constraints or economic considerations, it still has levers at its disposal to design and deploy an effective strategy aimed at reducing environmental impacts.

4.2. Limitations

4.2.1. Limitations of the Methodology

The methodological limitations inherent in our approach stem from the incomplete application of the entire LCA standard. The assessment of impact indicators was not supplemented by normalization and weighting procedures, which would have provided a synoptic overview of all categories and the explicitly revealed potential trade-offs. Finally, the life cycle analyses were carried out using a single characterization method. It is customary to perform two LCAs employing different characterization methods to verify the consistency of the results and reinforce the robustness of the assessment. Furthermore, the uncertainty associated with the impact indicator values was not assessed, which makes our conclusions somewhat fragile.

4.2.2. Limitations of Datacenter Infrastructure and Cloud Impact Assessment

The selected use case does not accurately reflect the industrial reality of manufacturing organizations. In industrial environments, the impact of datacenter infrastructure and cloud service will be greater. For example, deploying a PLM system architecture for 10,000 registered users can require 100 TB of storage, which is 100 times higher than the cloud service considered in our use case. The methodology remains applicable to industrial PLM systems; however, the impact results obtained for PLM system components must be balanced before being generalized or extrapolated. Another limitation concerns the impacts associated with the datacenter infrastructure taken into account. Our assessments highlighted the omission of several technical elements in the datacenter environment. These include transformers, backup batteries, diesel generators for power outages, uninterruptible power supplies, high-voltage cabling, cable trays, high-voltage switches, gas fire suppression systems, potential on-site power generation equipment, and finally, the manufacture of the cooling system. Furthermore, for the cloud services considered, this assessment does not take into account data replication, backups, or cloud infrastructure redundancy mechanisms that ensure service continuity. These two limitations tend to offset the dominant impact of end-user equipment, shifting distribution towards a more bipolar model, as highlighted in recent reports on the subject [41].

4.2.3. Limitations of the Tools Used

The tool developed and used for collecting inventory data does not allow for the exclusive collection of primary data. This limitation stems from the nature of information relating to the PLM system architecture, which is both highly specific and dispersed throughout the organization. The use of this tool with a single IT architect, although directly related to the PLM system architectures studied, does not guarantee the collection of purely primary data. Consequently, assumptions had to be made, and secondary data was incorporated when responses were incomplete or unavailable.

4.3. Perspectives

4.3.1. Industrial

A monitoring tool dedicated to tracking user, network, and datacenter inventory data from the PLM system architecture could be implemented to replace expert testimony with primary data observed experimentally. Initiatives involving multiple data sources, interfaces, data extraction, data storage and unification, data visualization, and, finally, exploitation by LCA practitioners. This data process mining is illustrated in Figure 10.

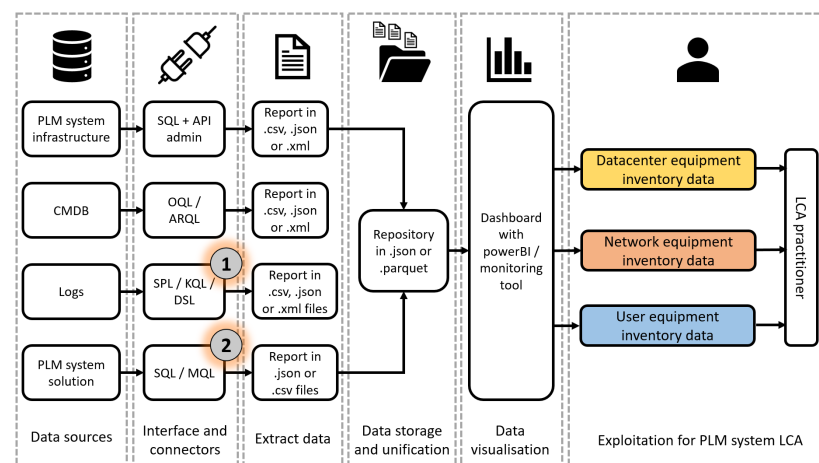


Figure 10. Primary data process mining concrete steps for LCA inventory data flows collection.

To illustrate our data process mining proposal, the «Interface and connectors» step for the «logs data source» in Figure 10 is detailed. The number 1 in Figure 10 refers to logs that can be configured to measure user connection times within the PLM system solution. If a user starts PLM system activities, this will then be visible thanks to the LOG IN OK event,

```
{
  "timestamp": "514835489",
  "timestamp_hr": "2017-04-25T08:00:00.254Z",
  "tenant_id": "",
  "client_ip": "10.10.10.10",
  "sso_id": "86086050D14661C32CBC29758270C57367550D1466573675",
  "user_id": "jcdcd54dr45rfezdc54d45ezedz5dez54",
  "event_name": "LOGIN_OK",
  "event_success": "0",
  "data": {"message": "User has successfully signed in"}
}
```

If a user stops PLM system activity, this will be visible through the LOG OUT OK event,

```
{
  "timestamp": "514835489",
  "timestamp_hr": "2017-04-25T12:00:00.254Z",
  "tenant_id": "",
  "client_ip": "10.10.10.10",
  "sso_id": "86086050D14661C32CBC29758270C57367550D1466573675",
  "user_id": "jcdcd54dr45rfezdc54d45ezedz5dez54",
  "event_name": "LOGIN_KO",
  "event_success": "0",
  "data": {"message": "User has successfully signed out"}
}
```

To illustrate our data process mining proposal, the number 2 in Figure 10 is detailed below. MQL (Matrix Query Language) commands are a powerful tool for extracting structured information stored in the system. These commands allow users to retrieve specific business objects, select relevant attributes, and access historical data, enabling comprehensive analysis of the platform's content and usage.

For example, extracting VPMReference objects from multiple collaborative projects using the following MQL commands «temp query bus VPMReference * * where "project == 'Sustainable PLM'" select name physicalid owner history». In this query, the «temp query bus» command searches for all instances of the VPMReference business object in a specified project. The conditional clause «where» limits the search to a particular collaborative space, such as 'Sustainable PLM'. By specifying selection parameters such as «name», «physicalid», and «owner, history», each query retrieves key metadata and the complete change history of the business objects. Once extracted, these datasets can be stored in structured formats such as .json or .csv. It is important to note that including the history attribute not only allows you to track changes to each object over time, but also to quantify the total storage volume associated with this historical data. By analyzing these records, it becomes possible

to visualize the storage volume of object data, identify modification patterns, and estimate the volume of gigabytes processed and stored in the platform.

The deliberate integration of a sophisticated data mining process aimed at meticulously refining input data for the LCA of PLM system architecture appears to be a particularly judicious and timely strategy, particularly in the context of the delicate transition from secondary datasets derived from testimonials to robust, empirical primary data. Such an improvement not only promises significantly increased reliability and scientific veracity of the underlying data but also enhances the analytical rigor of the resulting LCA conclusions. Conceptually, this undertaking is entirely feasible, but its practical implementation would inevitably entail a cascade of complex implications for both PLM system architecture and the process mining architecture. Deployment would require advanced algorithmic frameworks, resilient and scalable storage architectures, and rigorous validation pipelines. Intensive computing throughput and increased network operations would inevitably lead to increased energy consumption and digital environmental footprint, thereby paradoxically amplifying the environmental pressures that LCA aims to eliminate and mitigate. Furthermore, the aggregation and processing of highly granular personal or operational data could potentially conflict with GRPD regulations.

In essence, while improving data quality undeniably enhances the robustness and the credibility of the environmental assessment, it also accentuates the impact of digital manufacturing and the energy requirements inherent in its execution. Consequently, this data mining process illustrates a contemporary embodiment of the Jevons paradox, in which the ecological design of the PLM system, sustainable product innovation, and digital service unintentionally amplify the environmental burdens they seek to alleviate, placing industrial progress in a nuanced and paradoxical relationship between technological aspiration and ecological consequences.

4.3.2. Future Research Direction

Our future research trajectory aims to apply this methodology to a wider range of use cases, thus encompassing a broader spectrum of environmental impact categories. Social and economic impacts of ICT still represent a gap in research [22]. Furthermore, the ambition is to extend this methodology beyond the decision-making phase and to link, through the guiding principles of eco-design, low-tech innovation, and circular approaches, a wider range of technical solutions and impact mitigation scenarios, applicable not only to PLM systems but more broadly to complex IT infrastructures.

5. Conclusions

PLM systems are an essential technological lever for eco-design and are increasingly used to reduce the environmental footprint of manufactured products [42]. However, accurately identifying their own environmental impacts is a prerequisite for optimizing their role in the ecological transition. This article responds to this need by presenting not only quantified results on mandatory environmental indicators of the digital systems, but also a structured and transparent methodology based on life cycle assessment. This approach facilitates rigorous impact assessment and supports the development of targeted mitigation strategies through scenario analysis. These scenarios and strategies are contemporary and take a holistic view of the IT architecture of the PLM system, remote working policies, professional mobility models, as well as the sustainable design and organization of employee workplaces.

In terms of use case results, the manufacturing and usage phases of the PLM system architectures appear to be the first and second contributors to climate change, acidification, and depletion of abiotic minerals and metal resources. For ionizing radiation, the order

is reversed, and for fine particle emissions, it is the end-of-life and manufacturing phase that successively contributes the most. In terms of PLM system architecture components, user equipment dominates the contribution to all environmental impact considered, with the exception of particulate matter, where the impact comes from network equipment. Consequently, impact reduction strategies should be sequentially targeted at these stages and components. Once these hotspots have been identified, the manufacturing and use phases of user equipment, particularly desktop central units and dual-screen configurations commonly used in PLM-related business units, appear to be strategic points of intervention. Extending their lifespan, when accompanied by purchasing and sales policies that promote the reconditioning of IT equipment upstream and downstream the usage phase, appears to be a truly effective lever for reducing these environmental impacts. It seems to be the most effective, remains independent of the initial IT architectural choices of the PLM system, and can be implemented consistently across manufacturing organizations. Conversely, the effectiveness of impact reduction achieved through scenarios such as the relocation of datacenters to regions with a more sustainable electricity mix or adopting a diversified portfolio of sustainable mobility options by users remains dependent on architectural choices. The reductions achieved are often smaller, or even non-existent in some cases, due to their exclusive focus on the use phase.

This overview of the relative environmental impacts of PLM system components allows formalization to highlight current gaps and challenges in the field of impact data, particularly with regard to IT components. The need to model component datasets with LCA software tools appears to be a key factor in successfully conducting these assessments, not only for PLM system architecture but also for digital infrastructures in general. Nevertheless, this study also laid the groundwork for the development of two preliminary tools, designed to evolve and be reused for the identification, assessment, and mitigation of environmental impacts, both within PLM systems architectures and, more broadly, across all digital systems. These tools include (i) an online questionnaire for collecting inventory data, intended for deployment to IT architects overseeing the implementation of PLM systems, and (ii) a calculation and visualization tool, based on the calculation formulas detailed in the Appendix A, which complies with the LCA methodological standard while taking into account the specificities of environmental impact assessment in the digital domain.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17209279/s1>, File S1: BOM_and_Environmental_indicators_results.

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Appendix A. Inventory and Impact Data Integration

Appendix A.1. Pivotal Formulas

$$L_{f,eq} = L_{p,eq} + L_{v,eq} \frac{Q_{v,eq}}{Q_{t,eq}} + L_{\delta,eq} \frac{Q_{\delta,eq}}{Q_{t,eq}} P + L_{\rho} \frac{Q_{\rho,eq}}{Q_{t,eq}} \quad (A1)$$

$$C_{PLM} = \frac{1}{5} \sum_{i=T1}^{T5} C_{day,i} C_{pro,i} C_{per,i} \quad (A2)$$

$$Q_{<>} = \frac{Q_d Q_c T_d}{T_a} C_{PLM} C_{rw} \quad (A3)$$

$L_{f,eq}$ —final lifespan used for calculating equipment environmental impact

L_p —lifespan planned by Arts et Métiers Institute of Technology

Q_t —total quantity of equipment

L_v, Q_v —average upstream refurbishment lifespan, quantity of equipment concerned

L_{δ}, Q_{δ} —average downstream refurbishment lifespan, quantity of equipment concerned

L_{ρ}, Q_{ρ} —average re-use lifespan, quantity of equipment concerned

C_{PLM} —PLM allocation ratio for network equipment, workplaces, and commutes

$C_{day,eq}$ —user equipment usage coefficient within the total number of daily connections

$C_{pro,eq}$ —PLM system user equipment usage coefficient within professional activities

$C_{pers,eq}$ —PLM system user equipment usage coefficient within personal activities

$Q_{<>}$ —average number of commutes imputed to the PLM system per user per year

Q_d —quantity of days of PLM system use

Q_c —average quantity of connections per day

T_c —average duration per connection in hours

T_a —average accessibility window of CAD rooms

C_{rw} —average remote working coefficient per PLM user

Appendix A.2. PLM System Parts Manufacturing Phase Impact Formulas

$$R_{01,eq,cat} = Q_{t,eq} \frac{L_{i,eq}}{L_{f,eq}} C_{day,eq} C_{pro,eq} C_{per,eq} I_{eq,m,cat} \quad (A4)$$

$$R_{01,eq,cat} = Q_{t,eq} \frac{L_{i,eq}}{L_{f,eq}} C_{PLM} I_{eq,m,cat} \quad (A5)$$

$$R_{01,eq,cat} = Q_{t,eq} \frac{L_{i,eq}}{L_{f,eq}} I_{eq,m,cat} \quad (A6)$$

$R_{01,eq,cat}$ —manufacturing impact results by impact category and equipment category

$L_{i,eq}$ —lifespan used in the impact data for the equipment category

$I_{eq,m,cat}$ —impact data of equipment manufacturing phase by impact category

Appendix A.3. PLM System Parts Distribution Phase Impact Formulas

$$R_{02,eq,cat} = \frac{Q_{t,eq} M_{eq}}{L_{f,eq}} C_{day,eq} C_{pro,eq} C_{per,eq} \sum_{i=1}^{IV} D_i C_{i,eq} I_{i,cat} \quad (A7)$$

$$R_{02,eq,cat} = \frac{Q_{t,eq} M_{eq}}{L_{f,eq}} C_{PLM} \sum_{i=1}^{IV} D_i C_{i,eq} I_{i,cat} \quad (A8)$$

$$R_{02,eq,cat} = \frac{Q_{t,eq} M_{eq}}{L_{f,eq}} \sum_{i=1}^{IV} D_i C_{i,eq} I_{i,cat} \quad (A9)$$

$R_{02,eq,cat}$ —distribution impact results by impact category and equipment category
 M_{eq} —mass of an equipment category
 D_i —distance travelled by transport mode i
 $C_{i,eq}$ —coefficient for the scenario using transport mode i per equipment category
 $I_{i,cat}$ —distribution impact data by impact category and transport mode i

Appendix A.4. PLM System Parts Usage Phase Impact Formulas

$$R_{03,T,cat,loc} = Q_d Q_c T_c C_{day,eq} C_{pro,eq} C_{per,eq} P_{eq} I_{lowV,cat,loc} \quad (A10)$$

$$R_{03,R,cat,loc} = K C_{PLM} Q_{t,eq} P_{eq} I_{lowV,cat,loc} \quad (A11)$$

$$R_{03,R4,cat,loc} = K C_{PLM} Q_{t,eq} P_{eq} I_{medV,cat,loc} \quad (A12)$$

$$R_{03,D1,cat,loc} = K F_l (F_{PUE} - 1) P_{IT} I_{highV,cat,loc} \quad (A13)$$

$$R_{03,D2,cat,loc} = K F_l P_{IT} I_{highV,cat,loc} \quad (A14)$$

$$R_{03,D3,cat} = N_{GB} I_{s,cat} \quad (A15)$$

$$R_{03,Tr1,cat} = Q_d C_{PLM} T_a Q_r P_r I_{lowV,cat,loc} \quad (A16)$$

$$R_{03,Tr2,cat} = Q_{<>} D_u \sum_{i=a}^g C_i I_{i,cat,loc} \quad (A17)$$

$R_{03,T,cat}$ —usage impact results by impact category and user equipment (T)
 P_{eq} —power requirement for the electrical supply of the equipment in kW
 $I_{lowV,cat,loc}$ —impact data of 1 low-voltage kWh by location and impact category
 $R_{03,R,cat}$ —usage impact results by impact category and network equipment (R)
 K —a constant number of hours per year
 $R_{03,R4,cat}$ —usage impact results by impact category for fiber optic (R4)
 $I_{medV,cat,loc}$ —impact data of 1 medium-voltage kWh by location and impact category
 $R_{03,D1,cat}$ —usage impact results by impact category for datacenter building (D1)
 F_l —load factor
 F_{PUE} —PUE factor
 P_{IT} —installed IT power in kW
 $I_{highV,cat,loc}$ —impact data of 1 high-voltage kWh by location and impact category
 $R_{03,D2,cat}$ —usage impact results by impact category for datacenter IT equipment (D2)
 $R_{03,D3,cat}$ —usage impact results by impact category for cloud service (D3)
 N_{GB} —amount of data stored over one year
 $I_{s,cat}$ —impact category factor of the LCI for the service «Storing 1 GB of data in the cloud via a fixed-line connection for one year.»
 Q_r —quantity of CAD rooms
 P_r —power required for lighting, air conditioning, and heating of one 30 m² room
 D_u —average distance travelled by a user per year
 C_i —coefficient share of transport mode i for commuting between home and work
 $I_{i,cat,loc}$ —transport mode i impact data by location and impact category

Appendix A.5. PLM System Parts End-of-Life Phase Impact Formulas

$$R_{04,eq,cat} = \sum_{i=\mu}^{\eta} R_{04,i,eq,cat} \quad (A18)$$

$$R_{04,\mu,T,cat} = Q_{v,eq} \frac{L_{i,eq}}{L_{f,eq}} C_{day,eq} C_{pro,eq} C_{per,eq} C_{\mu,eq} I_{m,eq,cat} \quad (A19)$$

$$R_{04,\mu,R,cat} = Q_{v,eq} \frac{L_{i,eq}}{L_{f,eq}} C_{PLM} C_{\mu,eq} I_{m,eq,cat} \quad (A20)$$

$$R_{04,\mu,D2,cat} = Q_{v,eq} \frac{L_{i,eq}}{L_{f,eq}} C_{\mu,eq} I_{m,eq,cat} \quad (A21)$$

$$R_{04,\xi,T,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\xi,eq} \frac{M_{eq}}{L_{f,eq}} C_{day,eq} C_{pro,eq} C_{per,eq} (D_{\xi} I_{IV,cat,loc} + I_{\xi,eq,cat}) \quad (A22)$$

$$R_{04,\xi,R,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\xi,eq} \frac{M_{eq}}{L_{f,eq}} C_{PLM} (D_{\xi} I_{IV,cat,loc} + I_{\xi,eq,cat}) \quad (A23)$$

$$R_{04,\xi,D2,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\xi,eq} \frac{M_{eq}}{L_{f,eq}} (D_{\xi} I_{IV,cat,loc} + I_{\xi,eq,cat}) \quad (A24)$$

$$R_{04,\lambda,T,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\lambda,eq} \frac{M_{eq}}{L_{f,eq}} C_{day,eq} C_{pro,eq} C_{per,eq} (D_{\xi} I_{IV,cat,loc} + I_{\beta,eq,cat} + I_{\lambda,eq,cat}) \quad (A25)$$

$$R_{04,\lambda,R,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\lambda,eq} \frac{M_{eq}}{L_{f,eq}} C_{PLM} (D_{\xi} I_{IV,cat,loc} + I_{\beta,eq,cat} + I_{\lambda,eq,cat}) \quad (A26)$$

$$R_{04,\lambda,D2,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\lambda,eq} \frac{M_{eq}}{L_{f,eq}} (D_{\xi} I_{IV,cat,loc} + I_{\beta,eq,cat} + I_{\lambda,eq,cat}) \quad (A27)$$

$$R_{04,\eta,T,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\eta,eq} \frac{M_{eq}}{L_{f,eq}} C_{day,eq} C_{pro,eq} C_{per,eq} ((D_{\xi} + D_{\eta1}) I_{IV,cat,loc} + D_{\eta2} I_{I,cat,loc} + I_{\eta,eq,cat}) \quad (A28)$$

$$R_{04,\eta,R,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\eta,eq} \frac{M_{eq}}{L_{f,eq}} C_{PLM} ((D_{\xi} + D_{\eta1}) I_{IV,cat,loc} + D_{\eta2} I_{I,cat,loc} + I_{\eta,eq,cat}) \quad (A29)$$

$$R_{04,\eta,D2,cat} = (Q_{t,eq} - Q_{v,eq}) C_{\eta,eq} \frac{M_{eq}}{L_{f,eq}} ((D_{\xi} + D_{\eta1}) I_{IV,cat,loc} + D_{\eta2} I_{I,cat,loc} + I_{\eta,eq,cat}) \quad (A30)$$

$R_{04,eq,cat}$ —end-of-life impact results by impact category and equipment category

$R_{04,\mu,T,cat}$ —re-manufacturing impact results by impact category and user equipment (T)

$C_{\mu,eq}$ —re-manufacturing impact data coefficient comparing manufacturing phase

$R_{04,\mu,R,cat}$ —re-manufacturing impact results by impact category and network equipment (R)

$R_{04,\mu,T,cat}$ —re-manufacturing impact results by impact category and datacenter IT equipment (D2)

$R_{04,\xi,T,cat}$ —recycling impact results by impact category and user equipment (T)

$C_{\xi,eq}$ —recycling coefficient of end-of-life equipment exiting the life cycle.

D_{ξ} —average distance through recycling center from PLM system workplaces

$I_{IV,cat,loc}$ —freight lorry transport mode impact data by location and impact category

$I_{\xi,eq,cat}$ —impact data of equipment recycling by impact category

$R_{04,\xi,R,cat}$ —recycling impact results by impact category and network equipment (R)
 $R_{04,\xi,D2,cat}$ —recycling impact results by impact category and datacenter IT equipment (D2)
 $R_{04,\lambda,T,cat}$ —incineration and landfilling impact results by impact category and user equipment (T)
 $C_{\lambda,eq}$ —landfilling coefficient of end-of-life equipment exiting the life cycle.
 $I_{\beta,eq,cat}$ —impact data of equipment incineration by impact category
 $I_{\lambda,eq,cat}$ —impact data of equipment landfill by impact category
 $R_{04,\lambda,R,cat}$ —incineration and landfilling impact results by impact category and network equipment (R)
 $R_{04,\lambda,D2,cat}$ —incineration and landfilling impact results by impact category and datacenter IT equipment (D2)
 $R_{04,\eta,T,cat}$ —re-exportation impact results by impact category and user equipment (T)
 $C_{\eta,eq}$ —re-exportation coefficient of end-of-life equipment exiting the life cycle.
 $D_{\eta1}$ —average distance through port from recycling center
 $D_{\eta2}$ —distance through IT equipment dump from port
 $I_{\lambda,eq,cat}$ —impact data of equipment savage dumping by impact category
 $R_{04,\eta,R,cat}$ —re-exportation impact results by impact category and network equipment (R)
 $R_{04,\eta,D2,cat}$ —re-exportation impact results by impact category and datacenter IT equipment (D2)

Appendix B. Environmental Impact Categories Classification and Characterization

Table A1. Environmental footprint 3.1 classification and characterization, European Commission, July 2022.

Environmental Impact Categories	Indicator	Model	Unit	End-Point
Climate change	Radiative forcing as Global Warming Potential (GWP100)	IPCC 2013, GWP100 [43]	kg CO ₂ eq	Climate change
Acidification	Accumulated Exceedance (AE)	Posch et al. (2008) [44], Seppälä et al. (2006) [45]	mol H ⁺ eq	Ecosystem
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystem (CTUe)	USEtox Rosenbaum et al. (2008) [46]	CTUe	Ecosystem
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	Posch et al. (2008) [44], Seppälä et al. (2006) [45]	kg N eq	Ecosystem
Eutrophication, freshwater	Fraction of nutrients reaching marine end compartment (P)	Struijs et al. (2009) [47]	kg P eq	Ecosystem
Eutrophication, terrestrial	Accumulated Exceedance (AE)	Struijs et al. (2009) [47]	mol N eq	Ecosystem
Particulate matter	Human health effects associated with exposure to PM _{2.5}	Fantke et al. (2016) [48]	Disease incidence()	Human Health
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	USEtox Rosenbaum et al. (2008) [46]	CTUh	Human Health
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	USEtox Rosenbaum et al. (2008) [46]	CTUh	Human Health
Ionizing radiation	Human exposure efficiency relative to U ²³⁵	Frischknecht et al. (2000) [49]	kBqU ₂₃₅ eq	Human Health

Table A1. Cont.

Environmental Impact Categories	Indicator	Model	Unit	End-Point
Ozone depletion	Ozone Depletion Potential (ODP)	World Meteorological Organization (1999) [50]	kg CFC – 11 eq	Human Health
Photochemical ozone formation	Tropospheric ozone concentration increase	Van Zelm et al. (2008) [51] ReCipe (2008) [47]	kg NMVOC eq	Human Health
Land use	Soil quality index (Biotic production, Erosion resistance, Mechanical filtration, Groundwater replenishment)	Beck et al. (2010) [52] LANCA, Bos et al. (2008) [53]	pt	Resources
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	van Oers et al. (2002) [54], in CML, v4.8 (2016)	MJ	Resources
Resource use, minerals and metals	Abiotic resource depletion—(ADP ultimate reserves)	van Oers et al. (2002) [54], in CML, v4.8 (2016)	kg Sb eq	Resources
Water scarcity	Resources	AWARE 100, based on Boulay et al. (2018) [55]	m ³ world eq	Resources

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