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Assessing Material and Waste Flows at POLIMI: A Procurement-Based Empirical Analysis

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Abstract

This thesis investigates whether procurement spending data, when cleaned, reclassified by waste stream, and clustered, can serve as a proxy for estimating material waste generation at POLIMI. The study is motivated by the absence of a clear, unified public environmental data infrastructure at the institution, where procurement and waste records are held in incompatible systems with no shared classification logic. To structure the analysis, five environmental Concepts and a Stream Logic were defined, establishing explicit boundary decisions governing which flows fall within scope.

Two primary results were produced: a Waste Typology organizing fourteen waste fractions according to Italian regulatory categories and operational management channels, and a harmonized procurement dataset consolidating 19.457 records into 209 CPV groups covering 2020 to 2024. The proxy method was tested against four waste streams: Bulky Waste, Municipal Paper, WEEE, and Hazardous Special Waste. Three streams produced estimates in close alignment with measured waste data, while WEEE showed a substantially larger divergence, attributable to the considerable heterogeneity of its items and a temporal lag between procurement and disposal.

The study concludes that procurement-based proxies are valid for physically discrete, auditable waste categories with grounded conversion factors, and less reliable for long-life equipment without life cycle corrections. The results offer a documented baseline applicable to future environmental inventory work at POLIMI and comparable decentralized institutions.

Keywords: procurement proxy; organizational life cycle assessment; waste typology; material flow; waste electronical and electrical equipment; common procurement vocabulary; university environmental; assessment; input-output matching

Abstract in Italiano

Questa tesi indaga se i dati di approvvigionamento per gli acquisti, una volta armonizzati, possano fungere da proxy per stimare la produzione di rifiuti materiali presso il POLIMI. Lo studio nasce dall'assenza di un'infrastruttura ambientale unificata all'interno dell'Ateneo, dove i registri degli acquisti e quelli dei rifiuti sono conservati in sistemi incompatibili e privi di una logica classificatoria condivisa. Per strutturare l'analisi sono stati definiti cinque Concetti ambientali e una logica a flusso ('Stream logic'), per definire il perimetro analitico.

Sono stati prodotti due risultati principali: una Tipologia dei Rifiuti che organizza quattordici frazioni secondo le categorie normative italiane e i canali operativi di gestione, e un dataset armonizzato degli acquisti che consolida 19.457 record in 209 gruppi CPV relativi al periodo 2020-2024. Il metodo proxy è stato testato su quattro flussi: Rifiuti Ingombranti, Carta Municipale, RAEE, e Rifiuti Speciali Pericolosi. Tre flussi hanno prodotto stime molto vicine ai dati misurati, mentre per i RAEE è emerso uno scostamento significativamente più ampio, attribuibile alla forte eterogeneità degli articoli e al ritardo temporale tra l'acquisto delle apparecchiature e la loro dismissione.

Lo studio mostra che i proxy basati sugli acquisti sono validi per categorie di rifiuto fisicamente distinguibili, tracciabili e supportate da fattori di conversione solidi, mentre risultano meno affidabili per apparecchiature a lunga vita utile in assenza di correzioni legate al ciclo di vita. I risultati offrono una base documentata applicabile a futuri lavori di inventario ambientale presso il POLIMI e in istituzioni decentralizzate analoghe.

Parole chiave: proxy di approvvigionamento; analisi del ciclo di vita organizzativa; tipologia dei rifiuti; flusso materiale; rifiuti di apparecchiature elettriche ed elettroniche; vocabolario comune per gli appalti; valutazione ambientale universitaria; analisi input output

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Introduction

POLITECNICO DI MILANO (POLIMI) is a large institution composed of 48.383 students and 3.100 academic and administrative staff across six Italian campuses plus one in China, and operates like a vast “factory” forming professionals and driving cutting-edge research [1]. Being a large institution and holding the responsibility of being one of the primary repositories of culture, it carries a profound responsibility in the transmission of knowledge as it can directly contribute to the diffusion of a sustainability culture [2]. Beyond this, adopting sustainability principles at its core allows an institution like POLIMI to legitimize business strategies and eventually build trust in relationships through transparent communication [2].

Along these lines, after a series of sustainable but rather fragmented initiatives, POLIMI’s efforts evolved and converged into the launch of its first Sustainability Strategic Plan 2023-2025 on October 23rd, 2023 as the natural continuation of the University’s 2023-2025 Strategic Plan, with the aim of leading society’s transformation towards sustainable development, “starting by putting the own house” in order (leading-by-example) to then contribute to a broader vision of collective responsibility within the European academic landscape [3], [4], [5].

To move from these strategic intentions to actions, one of the relevant steps POLIMI took was the launch at the end of 2024 of the POLIMI LCA Network [4]. This network allows different researchers to work together to apply the Life Cycle Assessment, which is a systematic approach to evaluate environmental footprints, to support the scientific evaluations underlying POLIMI’s operational decisions.

However, while this network provides expertise and experience, conducting a comprehensive environmental assessment of the institution as a whole remains a complex challenge. The most rigorous frameworks available for this purpose are the Organizational Life Cycle Assessment (O-LCA), defined under ISO 14072, and the related Organization Environmental Footprint (OEF), both of which adapt the well-established LCA methodology for the evaluation of the full environmental footprint of an organization rather than a single product. For a university like POLIMI, the application of an O-LCA or OEF would offer a systemic, evidence-based map of all reference flows across campuses and operations. Yet, despite the ambition, a full O-LCA at POLIMI currently remains out of reach, largely due to the fact that the methodological and data infrastructure to support one has not yet been established.

As explained by Lo-Iacono-Ferreira et al., this complexity mainly lies in the decentralization of management and operational control [6], which shows how there is often no centralized system to properly track the environmental data of supplies, with more emphasis on material supplies. The result then is a fragmented data landscape where records such as procurement records, waste flows and operational activities are tracked, when tracked at all, in incompatible formats across departments.

It is precisely within this fragmented data landscape that this thesis positions itself. Rather than attempting to conduct an O-LCA, it asks a more targeted empirical question: can procurement spending data, when cleaned, reclassified by waste stream, and clustered by material type, serve as a meaningful proxy for estimating material waste generation in a complex decentralized university like POLIMI? The answer to this question also requires addressing a necessary follow-up question: what steps are needed to make a procurement-to-waste mapping feasible and defensible when institutional data is fragmented, inconsistently coded, and spread across incompatible systems?

To make the analysis traceable, the thesis first establishes the analytical vocabulary and boundary decisions that govern it through the five environmental Concepts, a Stream Logic (S1-S5), and an Operational Perimeter, which jointly make explicit the reasoning behind which flows belong to POLIMI's inventory and why. Within this structure, two main activities were carried out. First, the procurement records were reclassified and organized, producing 209 harmonized groups from which waste-relevant fractions can then be systematically identified and screened; and the waste data available at POLIMI was structured into a Waste Typology aligned with Italian regulation. Second, the proxy method was tested empirically across four real waste streams, with results reporting the degree of alignment between procurement-based estimates and measured waste data for those where measured figures were available and more complete.

The argument develops step by step. Chapter 1 surveys the literature and clarifies the methodological gap that motivates the study. Chapter 2 presents the analytical vocabulary and boundary decisions used to organize the study, including the definition of Concepts, Streams, the Operational Perimeter, and the data strategy. Chapters 3 and 4 present the two data artefacts that represent the output and input sides. Chapter 5 brings these elements together through the input-output matching workflow and reports the proxy comparison results. Lastly, Chapter 6 interprets the evidence, acknowledges limitations, and draws the main conclusions.

1 Literature Review & Background

1.1. Universities as operations systems

By definition, a factory is a building or set of buildings where large amounts of goods are produced mainly through machines [7]. Under this strict definition, an organization such as a university would not be considered a factory per se, since it does not produce a tangible good. Nonetheless, when interpreted more broadly, one could argue that a university is a system composed of "many small factories" and that the institution itself may be viewed, from certain perspectives, as a factory whose "product" is the professionals who later enter the labour market [8], [9].

In this functional sense, POLIMI can be interpreted as a factory in operational terms as it receives inputs (students, workers, energy, materials), performs structured processes (teaching, research, laboratories) and generates transformed outputs (graduates, knowledge, services, and waste).

This aligns with the transformation model of operations, which states that operations transform inputs into outputs through organized processes, and that this logic applies equally to manufacturing and service organizations. Therefore, from a process-engineering viewpoint, any organization such as a university fits the definition functionally despite not being an industrial production site [8].

This functional perspective was further formalized for the university's environmental management through the Input-Output logic proposed by Perotto [9]. Developed at POLIMI's own Quality Centre, this framework serves as the primary inspiration for the present study, by tracking the entries and exits of matter and energy to identify environmental aspects [9]. By adopting this model, the university is treated as a transformation system where materials procurement records (inputs) can be linked directly to waste generation (outputs) [9].

Viewing the university as a system also requires attention to its physical and infrastructural dimension. Universities operate large, resource-intensive campuses whose buildings, materials and maintenance activities carry impactful environmental and organizational implications. Like any large operational system, universities generate negative externalities as a by-product of their core activities, making environmental management a relevant institutional concern. Hence, a sustainable higher education institution must ensure that the resources used to run its campus and engage with society do not compromise its regional or global environmental standing [10].

1.2. O-LCA and OEF

The understanding of this then raises a practical question: how can an institution verify that it is actually moving in the right direction? As the well-known management principle states, what gets measured, gets managed [11]; however, in the context of environmental management, this "measure" constitutes one of the greatest difficulties for organizations, as a correct evaluation depends entirely on the selection of adequate raw data and the reliability of the relationships established between them [12]. Consequently, universities need structured ways to evaluate, compare and report their environmental performance to ensure their actions genuinely support sustainability goals. In practice, for organizations such as POLIMI, among the available approaches for assessing environmental performance, the most complete ones are the Organizational Life Cycle Assessment (O-LCA) and the Organization Environmental Footprint (OEF). Both were designed to prevent burden shifting by considering environmental impact categories across several dimensions. Their difference lies in their purpose and methodological approach. OEF applies a prescriptive structure and therefore is better suited for comparative assessments across institutions, while O-LCA provides guidance that allows methodological choices, making it more appropriate for the identification of internal environmental hotspots.

D'Angelo et al., in a study included in [13], found no significant practical differences between O-LCA and OEF when applied to the same organization; therefore, the eventual choice of one for POLIMI would lie in whether the goal is the identification of internal hotspots or the production of results that could be compared with those of other institutions.

Whichever framework is selected, conducting such an assessment already reinforces the university's responsibility to manage its environmental impacts and provides the structured evidence required for certifications such as those aligned with ISO standards. Although an O-LCA or OEF does not constitute a certification on its own, it produces the type of multi-impact and systematic data that supports alignment with standards like ISO 14001 for Environmental Management Systems and ISO 50001 for Energy Management; but certification itself demands many more steps that fall outside the scope of this thesis.

Since both mentioned frameworks are grounded in the methodological logic of Life Cycle Assessment (LCA), it is indeed important to briefly review its four stages. First there is the Goal and Scope definition, where the aim of the study and the unit of analysis are defined alongside key elements such as the reporting organization and flow, plus the system boundary. Second, the Life Cycle Inventory where all the activities within the system boundary are identified and the data collection on resource use and emissions is documented. Third, the Life Cycle Impact Assessment, which develops the translation of the inventory data into potential environmental impacts through classification and characterization; and lastly, the Interpretation phase, where after checks for complete, sensitive and consistent data to ensure robust and reliable results, the identification of the environmental hotspots is made and explained in the conclusions [14]. However, it is important to remember that despite being named "steps or phases", these phases need not be followed in that order; the United Nations Environment Programme (UNEP) clarifies that these phases should be approached as an iterative process rather than a simple linear one as findings in one phase often can and should lead to revisions to other phases to ensure the accuracy and relevance of the study [15]. It is within this methodological framework that the present thesis operates, focusing specifically on the Life Cycle Inventory phase as the foundation for its empirical investigation of material and waste flows at POLIMI.

1.3. University Campus Assessments in the literature

Within this context, the existing literature applying LCA and similar assessment frameworks related to universities has grown in recent years, yet comprehensive evaluations of entire higher-education organizations remain relatively rare. Most studies focus on specific facilities, subsystems or activities rather than the full institutional footprint. The Brazilian case study on sustainable practices represented a clear example as it applied LCA to the replacement of disposable cups with reusable ones, but the assessment was restricted to that single action rather than the environmental performance of the whole university [16]. For the development of this thesis, seven studies across six countries (Spain, Switzerland, Turkey, Indonesia, United States and Iran) were identified as the closest examples of broader campus-level assessments and summarized below in Table 1.1.

Table 1.1: Comparative Table of University Environmental Assessments.

University & Country	Year	Institutional Scale	Framework Used	Assessment Scope	Assessed Areas	Boundary Approach	Data Retrieval Challenge
• Doing study: Abdullah Gul University (AGU). • Subject of study: Abdullah Gul University (Sumer Campus) - same institution. • Country: Turkey (Kayseri) [17].	• Pub: 2023. • Assessed: 2019.	• 1.968 total students; 364 total employees (219 academic, 145 admin). • Single campus (Sumer Campus): 53.208 m² building area. • Recently established public university.	• Life Cycle Sustainability Assessment (LCSA) integrating E-LCA, LCC, and S-LCA.	• Whole Sumer Campus (single campus study); building operations and facilities.	• Energy, Materials (Paper), Waste, Water, Transport: Explicitly assessed with data. • Land use: Mentioned (land area and green space %) but not fully quantified in impact results. • Social: Explicitly assessed via surveys for four stakeholders.	• “Gate-to-gate approach”. • “Cradle-to-gate approach”. (for cost) • “Use-phase analysis".	• Non-availability of data for urban/architectural features. • Long time needed for inventory collection. • Descriptive social data format prevented specific functional unit (S-LCA).

University & Country	Year	Institutional Scale	Framework Used	Assessment Scope	Assessed Areas	Boundary Approach	Data Retrieval Challenge
• Doing study: University of the Basque Country (UPV/EHU). • Subject of study: University of the Basque Country (UPV/EHU) - same institution. • Country: Spain [18].	• Pub: 2021. • Assessed: 2016.	• 39.360 students; 7.453 total staff (5.596 academic, 1.857 admin). • 3 main campuses; excludes hospital units, isolated research centres, and units with <25 users. • Public university.	• Organizational Life Cycle Assessment (O-LCA) (ISO 14072) and Organization Environmental Footprint (OEF).	• Almost whole institution (96,8% of total users); covers buildings and operational activities across 3 campuses.	• Energy, Materials (ICT/Paper), Waste, Water, Transport: Explicitly assessed with data. • Land use: Mentioned via "Ecosystems" impact but not fully quantified (uncertain). • Social: Explicitly assessed (accidents, child labour, illiteracy).	"Entire life cycle" perspective; includes an estimate for building construction (upstream).	• Unregistered fluxes. • Lack of separate building meters. • Difficult inventory compilation for buildings. • Data allocation problems for shared/isolated units.

University & Country	Year	Institutional Scale	Framework Used	Assessment Scope	Assessed Areas	Boundary Approach	Data Retrieval Challenge
• Doing study: Kocaeli University (Departments of Environmental and Chemical Engineering). • Subject of study: Kocaeli University (Umuttepe Main Campus) - same institution. • Country: Turkey (Kocaeli) [19].	• Pub: 2024. • Assessed: 2022.	• ~40.000 people: 37.633 full-time students, 994 academic staff, 921 admin staff. • Single campus (Umuttepe Main Campus); 938.646 m²; includes 12 faculties, 2 institutes, 1 vocational school. • State university focusing on education and research.	• Organizational Life Cycle Assessment (O-LCA) following ISO/TS 14072.	• Single campus (Umuttepe Main Campus); includes all buildings, academic units, and administrative/social facilities.	• Energy, Materials (Paper/Plastic/Metal/Glass), Waste, Water, Transport, Land use: All explicitly assessed with data. • Transport: Limited to university-owned shuttles and vehicles within campus boundaries.	• "Operational control approach"; also described as a "top-down approach" and "whole life cycle perspective".	• Complexity of defining a functional unit/system boundary for universities. • Limited data availability for student commuting and intercity business trips.

University & Country	Year	Institutional Scale	Framework Used	Assessment Scope	Assessed Areas	Boundary Approach	Data Retrieval Challenge
• Doing study: Clemson University (Department of Environmental Engineering & Earth Sciences). • Subject of study: Clemson University (Main Campus) - same institution. • Country: USA (South Carolina) [20].	• Pub: 2020. • Assessed: 2014.	• 21.857 total students (17.260 undergrad, 4.597 grad); 4.900 total employees (1.388 faculty, 208 admin, 3.304 staff). • Single campus (Main Campus); includes nearby conference centre and Wastewater Treatment Plant WWTP; excludes off-campus departments, remote facilities, and experimental forest. • Research university (R1 Carnegie classification).	• Consumption-based hybrid LCA (HLCA) approach (combining process analysis and economic input-output).	• Single campus (Main Campus); includes specific buildings and operational activities related to the main site only.	• Energy, Materials (Paper), Transport, Water: Explicitly assessed with data. • Waste: Partially assessed (only GHG emissions from waste/recycling transportation). • Land use: Not covered (experimental forest explicitly excluded). • Other: Refrigerants and Fertilizers explicitly assessed.	• "Streamlined LCA approach"; uses "cradle-to-gate", "cradle-to-consumer", and "cradle-to-grave" for various Scope 3 sources.	• Data unavailability for remote campuses. • Lack of specific data for facility vehicles/golf carts. • Aggregated student travel expense records. • Missing gas chromatography results after 3 months, which limits the chemical analysis needed to evaluate air or water quality.

University & Country	Year	Institutional Scale	Framework Used	Assessment Scope	Assessed Areas	Boundary Approach	Data Retrieval Challenge
• Doing study: Kharazmi University (Civil Engineering Department). • Subject of study: Kharazmi University (Karaj campus) - same institution. • Country: Iran (Karaj) [21].	• Pub: 2024. • Assessed: 2021-2022 (Inventory period; results projected over a 100-year operational period).	• 8.146 students and 504 faculty members (at Karaj campus). • Single campus (Karaj campus); excludes construction, maintenance, and campus vehicles. • Research and teaching university.	• Life Cycle Assessment (LCA); specifically, a "process-based technique" following ISO 14040.	• Single campus (Karaj campus); focuses on 200.576 m² of building area and operational activities.	• Energy, Materials (Catering/Labs), Waste (Solid/Sewage), Water: Explicitly assessed with data. • Transport: Not covered (explicitly placed outside system boundary). • Land use: Not covered.	• "Gate-to-gate model". • "Operational phase"; specifically, for a "100-year operation period".	• Absence of a national LCI database (reliance on European Ecoinvent). • No published data on university documents/site. • Difficult coordination across university departments. • Specific challenges gathering chemistry lab data.

University & Country	Year	Institutional Scale	Framework Used	Assessment Scope	Assessed Areas	Boundary Approach	Data Retrieval Challenge
• Doing study: Collaborative research between ZHAW (Institute of Natural Resource Sciences) and UASG (Department of Alpine Region Development). • Subject of study: University of Applied Sciences of the Grisons (UASG) - institution assessed. • Country: Switzerland (Chur) [22].	• Pub: 2025 (online 2024). • Assessed: 2019 (regular operations) and 2020 (pandemic impact).	• ~2.000 students (1.330-1.404 FTE); ~300 employees (245-256 FTE). • Whole university operation; 19.656 m² floor space. • Public university of applied sciences.	• Explicitly uses both Organizational LCA (ISO 14072:2014) and the Environmental footprint (EF) framework.	• Whole institution.	• Explicitly assessed with data: Energy, Materials (IT/Paper), Waste, Water, Transport, Gastronomy, and Land use: Assessment used 19 categories condensed into 6 "main activity areas". • Land use was 1 of 15 impact categories specifically assessed via the EF framework.	• Includes "indirect upstream and downstream" emissions (Scope 3). • Follows "attributional LCA" principles and the GHG Protocol.	• Lack of energy intensity data for data centres/videoconferencing providers. • Extensive coordination needed for primary data. • Difficulty tracing external dining habits.

University & Country	Year	Institutional Scale	Framework Used	Assessment Scope	Assessed Areas	Boundary Approach	Data Retrieval Challenge
• Doing study: Universitas Pelita Harapan (UPH). • Subject of study: Faculty of Science and Technology (FaST) at UPH - same institution. • Country: Indonesia (Karawaci, Jakarta region) [23].	• Pub: 2017. • Assessed: 2015.	• ~1.000 university employees; 1.220 students enrolled at the FaST faculty. • One faculty (FaST); partially includes swimming pool, dormitory, and garden. • Private university.	• O-LCA based on "Guidance on Organizational Life Cycle Assessment".	• One faculty (FaST) and specific common facilities (dormitory, pool, garden) as a pilot project.	• Energy, Material, Water, Transport: Explicitly assessed with data. • Waste: Explicitly assessed (limited to paper and e-waste). • Land use: Not covered.	• "Cradle-to-gate assessment".	• Inability to collect data directly from suppliers. • Poor management of water and waste data. • Reliance on modelling for production processes due to lack of primary supplier info.

Note. Reference numbers in the University & Country column correspond to the full bibliographic entries listed in the Bibliography. Studies are cited by the row they appear in; no separate in-text citation is required when the table is referenced as a whole.

Among the institutions reviewed, the University of the Basque Country represented the most structurally comparable case to POLIMI given its public status and multi-campus layout across three sites serving 39.360 students [18]. Kocaeli University provided a similar scale with 37.633 full-time students [19], although its operations were concentrated on a single main campus rather than a decentralized network. Clemson University, with approximately 21.857 students at a single main research campus [20], was relevant in scale relative to the smaller reviewed cases but operated in a considerably different national and regulatory context. The remaining studies, including the Swiss UAS, Kharazmi University, Abdullah Gul University and UPH Indonesia, operated at scales that were not directly comparable to POLIMI. Their relevance to the present thesis is therefore methodological rather than institutional.

Size comparability and methodological comprehensiveness do not always coincide in the reviewed literature, and for the purposes of this thesis the latter is at least as important as the former. The University of the Basque Country stood out on both dimensions simultaneously. In terms of scope, it was the only study that applied both O-LCA under ISO 14072 and OEF simultaneously, covering 96,8% of total institutional users across its campuses [18]. More specifically, regarding materials and waste, it was also the only study to employ multi-source data triangulation across billing records, interviews and service provider reports simultaneously [18], doing so across seven distinct waste fractions including hazardous waste, paper, WEEE, glass, organic and residual streams. This combination of institutional comparability and methodological comprehensiveness makes it the closest available benchmark in the literature for what a full organizational assessment at an institution like POLIMI would require.

Kocaeli University offered a complementary methodological reference, particularly for Waste Typology design: its classification of campus waste into organic, inorganic and toxic fractions, supported by foreground data provided directly by the university and uncertainty quantification through Monte Carlo simulation [19], showed a level of methodological precision that could be replicated in an institutional context where raw data comes from multiple internal sources. The Swiss UAS, though operating at a much smaller scale, provided the most applicable precedent specifically for WEEE and IT equipment evaluation by approaching the modelling of IT assets as a yearly proportion of a multi-year bulk purchase that converts institutional procurement cycles into annualized environmental flows [22], a logic that directly addresses the kind of multi-year equipment contracts present at POLIMI.

Among the remaining studies, Clemson University offered the most comparable methodological approach, using monetary expenditure records to estimate environmental impacts when physical quantity data were unavailable [20], thereby demonstrating the usefulness of administrative financial data as a meaningful proxy in an institutional context. The tools differed, but the underlying logic that spending data can stand in for direct measurement when the right classification architecture is in place is structurally analogous to the procurement-to-waste mapping documented in this thesis.

Taken together, the reviewed studies reveal both common patterns as well as recurring limitations across diverse national and institutional contexts. One notable finding across these reviewed studies was that energy consumption consistently emerged as the principal environmental burden in the impact profile of university campuses. Reported contributions ranged from approximately 80% of the total environmental burden at Kocaeli University [19] to nearly 99% of the global warming potential at Abdullah Gul University [17], with similar patterns observed at Kharazmi University, Clemson University and the University of the Basque Country [18], [20], [21]. This point of convergence across diverse universities and geographical contexts shows that energy use is the primary environmental hotspot in higher education institutions. Yet, despite the centrality of energy, the environmental implications of material use, and waste generation receive far less systematic attention, creating a gap that this thesis seeks to address.

Another notable pattern across the reviewed studies concerned the definition of the system boundary. Most universities limited their assessment to the operational or use-phase of campus activities, adopting a gate-to-gate perspective that excludes construction and end-of-life stages of campus infrastructure. This was the case for Kharazmi and Abdullah Gul universities [17], [21], and it was similarly acknowledged by the University of the Basque Country, which relevantly noted that construction impacts were typically omitted due to inventory limitations [18]. This recurring focus on current operations reflects both methodological constraints and the practical need to rely on data that universities can effectively and consistently access and monitor. In line with this and as detailed in the following chapter, this thesis adopted a similar boundary, focusing on the on-site lifespan of materials from delivery to waste collection, where POLIMI has direct data access and management influence.

A third emerging pattern, and probably the most directly relevant to the motivation of this thesis, related to the prevalence of data gaps. Clemson University identified data unavailability as its largest obstacle in the research [20]; Kharazmi University similarly reported the absence of a national life cycle database [21], which led to the use of European datasets such as Ecoinvent, and it also noted the particular struggle in the collection of information from different university departments. The Swiss University of Applied Sciences highlighted the difficulty in drawing meaningful conclusions due to challenges obtaining information from providers of, for example, data centres [22]; while the University of the Basque Country noted reaching out to projections and "educated guesses" when data for specific centres was unavailable [18]. In response to these challenges, a consistent principle emerged: rather than approximating poorly documented flows, the reviewed studies chose to explicitly constrain their scope, grounding exclusions in operational control and organizational responsibility rather than data availability alone. These data challenges are not incidental and are just a few examples that reflect a structural problem in how universities track and manage environmental information, one that becomes even more pronounced in large, decentralized institutions.

1.4. The thesis in context

POLIMI presents precisely the above-mentioned structural challenge, with dispersed data sources complicating the development of a unified environmental inventory. Perlman's Materials Footprint study highlighted that although energy consumption is generally well-monitored, material procurement and waste handling remain insufficiently characterized, owing to the complexity and fragmentation of the available data [24]. This gap is especially notable given that POLIMI's own institutional reporting has explicitly framed waste production monitoring as a knowledge tool for understanding the economic and environmental impacts of its activities [25]. While this established a clear internal mandate, the university's data infrastructure has not yet been able to fully operationalize it. For instance, Intrieri (2015), in a study of POLIMI's waste system, illustrated this by noting that special waste data at POLIMI was derived entirely from the physical fourth copies of waste transfer forms (FIR) recovered from destination facilities, a system that was both labour-intensive and structurally incomplete, as it excluded waste streams handled by municipal operators who did not respond to data requests [26]. This is not a minor logistical detail but shows that while institutional willingness to monitor was present, the infrastructure required to do so effectively was not.

This imbalance raises the possibility that the dominance of energy use impact in campus-level assessments reflects data availability rather than actual environmental relevance. The difficulty reported by Kharazmi University in assembling even basic departmental information is echoed in a guide from York University explaining how organizations should structure and prioritize LCA data collection [27], which notes that data collection can account for 60% to 80% of the total time required for a study and that establishing solid data foundations is essential for producing reliable evaluations.

A related pattern emerged when looking at how the reviewed studies handled their administrative data sources. Most of them acknowledged using procurement records, billing data or operational reports as inputs, yet none of them documented the transformation logic that converted those sources into information ready to fill their environmental inventories. For a large and decentralized institution like POLIMI, where data systems were built for administrative rather than environmental purposes, this silence is not a minor gap.

When the path from institutional data to environmental insight is not made traceable, it becomes harder for other organizations to follow it, limiting how quickly these assessment practices could actually spread and reducing the positive spillovers that transparency could generate. This was precisely where this thesis positioned itself. Rather than treating the raw data transformation as background work, it made that reasoning the explicit object of study, documenting each step in a transparent and auditable way. This focus is important as the decisions in these areas always involve a degree of subjectivity, and only full transparency and traceability of the methods can prove their effective correctness and efficacy [28].

2 Objectives, Methodology & Conceptual Framework

2.1. Research objectives

The primary goal of this thesis was to respond to the following question: can procurement spending data, when cleaned, reclassified by waste stream, and clustered by material type, serve as a meaningful proxy for estimating material waste generation in a complex decentralized university like POLIMI? To answer this, this thesis pursued three main objectives.

- Make the analytical boundary reasoning of this thesis explicit and traceable, through a structured classification of POLIMI's environmental flows and the definition of the Operational Perimeter.
- Produce, from fragmented operation sources, the two inputs required to carry out the study: a reclassified procurement dataset and a Waste Typology organized according to Italian regulatory categories.
- Demonstrate empirical feasibility by testing how well procurement data reflects actual waste generation in the specific streams where measured data was available.

To support the objectives, this chapter defines the analytical vocabulary used to categorize the university's metabolism. These elements do not constitute a new theoretical framework for the field; rather, they represent the structured reasoning required to determine which flows belong to POLIMI's environmental inventory and why. The following sections introduce these elements named the five "Concepts" representing the environmental domains; the "Stream Logic" used to classify the detected flows within the campus; and their relationship.

2.2. The 5 Concepts

The literature reveals a consistent problem regarding the absence of structured data for inventory collection and quantification, making the inventory phase consistently reported as the most demanding part of the evaluation. When looking more closely at how different universities had approached the collection of data for this phase, the reviewed literature showed that almost all tracked some version of the five Concepts proposed in this section. Even if named differently or split up, all referred to at least two or three of these five Concepts, with each choice reflecting their local context and the flexibility of the official guidelines.

Hence, the five Concepts used in this study emerged from the empirical overlap across these studies, which were then filtered through what is currently relevant and feasible at POLIMI. The assessment carried out at the University of the Basque Country included in its inventory the consumption of energy and materials, and the generation of waste and transportation [18]; Kocaeli University, for its part, was also interesting because it explicitly included land use, which other studies skipped [19]; and AGU kept it simpler by considering just paper in the analysis regarding materials dimension [17]. Across different contexts and methodological approaches, these same environmental dimensions kept reappearing. Therefore, the five Concepts were derived from the convergence of this literature, structuring the data collection and analysis of the thesis.

O-LCA and OEF guidelines state that such an assessment is an environmental multi-impact approach, which means that a comprehensive set of environmental issues relevant for the specific system, in this case the university, should be considered, so that together they represent the potential environmental impact profile for the organization’s activities [15], [29]. On this basis, the five Concepts presented in this study were not merely labels but served as “environmental domains” borrowed from the recurring patterns observed across the literature. They served as a reading lens through which thousands of granular activities could be organized into a manageable inventory. Despite Transport appearing throughout their inventory phase in some of the reviewed studies discussed above, here it was not included as a Concept because it was considered to be a functional activity that consumes resources, whereas the five Concepts represent the environmental domains that capture the full metabolic flow of the organization, both inputs and outputs.

These five Concepts are Energy, Water, Material, Waste, and Land. Material refers to the goods, consumables and equipment entering the system, which form the basis of teaching, research and administrative functions. Waste captures the outputs produced as these materials are used. Energy covers the electricity, heating and other forms of power required to operate the buildings, laboratories and shared spaces, reflecting the dependence of the institution on external energy systems. Water includes all forms of intake and discharge, considering all uses of potable and technical water. And Land represents the physical area occupied by the university, involving buildings, paved surfaces and green spaces, framing how campus space is occupied, managed and transformed in relation to local biodiversity. Together, these five dimensions map the environmental landscape of an institution like POLIMI, presenting domains that, as shown above, are often considered when starting the inventory phase of a Life Cycle Assessment.

This reasoning was what made the inventory analytically tractable for this study, since it allowed data collection to be organized around high-level environmental domains rather than impractical enumeration of thousands of independent functions [30].

Organizing data collection around these five domains rather than around individual unit processes is both consistent with international guidelines, which recommend using aggregate flows crossing the organizational boundary rather than analysing every individual product [29], and with the academic practice of condensing wide-ranging university activities into a manageable set of main areas [22]. Breaking each Concept into sub-concepts then allows for greater precision where data is available without losing overall coherence. Together, they define what must be accounted for in the inventory.

2.3. The Stream Logic S1-S5

The Concepts clarified the environmental domains relevant to the assessment; however, they did not specify how flows actually enter and leave the university, leaving the inventory not yet operational. For instance, a kilogram of material may be purchased by POLIMI, brought by a student, embedded in a contracted service or left on campus for years before becoming waste. These differences matter for responsibility, boundary setting and data collection. This is why the "Streams" were introduced as a complementary layer that maps the detected flow pathways. In this thesis, this logic was used to make responsibility, data ownership and boundary decisions clear within POLIMI's decentralized environment where a single material can arrive via multiple institutional routes.

To make the inventory operational for this study, three practical criteria were defined to classify the flows observed at POLIMI and assign them to the appropriate stream. These criteria were not arbitrary but were informed by O-LCA standards and the previously mentioned input-output logic proposed for POLIMI by Perotto [9].

The first practical criterion used to classify flows was based on operational control, reflecting how POLIMI manages its activities and where data access is available. This approach follows the distinction established by Perotto between direct aspects (under control of the organization) and indirect aspects (mediated by external intermediaries such as contractors or users) [9]. According to International Consolidation standards, an organization exercises operational control when it holds the authority to set and enforce operating policies [29], [30], making it the preferred consolidation method for environmental assessment as it aligns responsibility with the ability to act. Thus, organizing the Streams around control ensured clarity over which activities POLIMI has real managerial influence and direct data access, strengthening the reliability of the inventory.

The second criterion considered the origin of each flow along POLIMI's value chain, distinguishing between what happens on-site versus upstream. Organizational LCA highlights that environmental impacts are not confined to what happens on campus, as many arise upstream in the production of the goods and services involved in the organization [15], making it important to maintain a clear separation between direct activities and indirect upstream contributions when defining the boundaries. The integration of origin criteria into the Streams definition allowed POLIMI to capture these distinctions and develop a more complete understanding of how the university's activities connect to the wider value chain.

Lastly, a third criterion accounted for the timing of flows. Organizational inventories must address the fact that they need to reconcile a one-year reporting interval with assets that persist far beyond that timeframe [15]. Methodological guidance indeed requires that burdens for long-lived assets account for their lifespan and the period over which they are used [15].

Taken together, the application of these three criteria resulted in five operational categories that helped to map the flows entering and leaving POLIMI's institutional boundary and are described in Table 2.1.

Table 2.1: Stream Logic.

Stream	Description	Input Origin	Time to Output	Output Type
S1 - Input with immediate output	Direct resources consumed quickly (e.g., water, energy).	Internal	Immediate	Waste, emissions
S2a - Purchased	Purchased short-life items (e.g., food, banners).	Internal purchases	< 1 year	Waste
S2b - User-Brought	User-brought short-life items (e.g., student food waste).	External (users)	< 1 year	Waste
S3 - Input with delayed Output	Long-life purchased goods (e.g., furniture, IT).	Internal purchases	> 1 year	Waste (delayed)
S4 - Contractor Input (Services)	Services creating indirect material outputs (e.g., cleaning, maintenance).	External (Outsourced services)	Variable	Waste, emissions
S5 - Digital Input	Digital services (e.g., cloud, streaming) - Intangible	External	Immediate	Emissions

Stream 1's purpose is to separate rapid-turnover flows from all other categories, since their environmental relevance lies in continuous operation rather than in material stock changes. Stream 2 ensures that short-life items are tracked consistently and not mixed with long-life assets represented by Stream 3; while its separation into S2a and S2b prevents misattribution of responsibility. Stream 4 exists to highlight the generation of material and emissions by contracted services, so they are not overlooked. Lastly, Stream 5 represents the category of intangible inputs whose environmental burdens arise through remote infrastructure rather than through physical flows on campus. Although these services do not generate material outputs, they do contribute to POLIMI's footprint through energy use and associated emissions. Including it as a separate stream acknowledges the growing relevance of digital services in organizational assessments and ensures that their impacts are not excluded simply because they lack physical form.

To better appreciate the usefulness of the Streams, we can take paper as an example. When the date for data collection comes, the person in charge could be assigned to collect data on paper flows for the inventory. However, the first question would be "which paper?" It could be the reams bought by the administration, or maybe the paper students bring and throw away on campus, or even the paper brought and used by the printing services operating on the campuses. They are all paper but with completely different owners, data sources and levels of responsibility for POLIMI. Without Streams, the data collector mixes all three together and either overcounts the university's responsibility or has no idea what to exclude. Using the Streams made the answer more immediate: administration paper is S2a and goes to procurement records, student paper is S2b and needs assessment to determine whether it falls under scope, and contractor paper is S4 and goes to service contracts. As illustrated, the Stream Logic makes the attribution of responsibility and the identification of the corresponding data source explicit before any collection begins.

2.4. Concept-Stream mapping table

Having defined Concepts and Streams independently, the following Table 2.2 makes their relationship explicit, showing which streams contribute to each environmental domain and on what basis.

This mapping, also visually supported by the Radial diagram in Figure 2.1 and the Input-Output diagram in Figure 2.2, provides the full picture of POLIMI's institutional flows before the Operational Perimeter narrows the scope to what has been analytically chosen to include in this thesis.

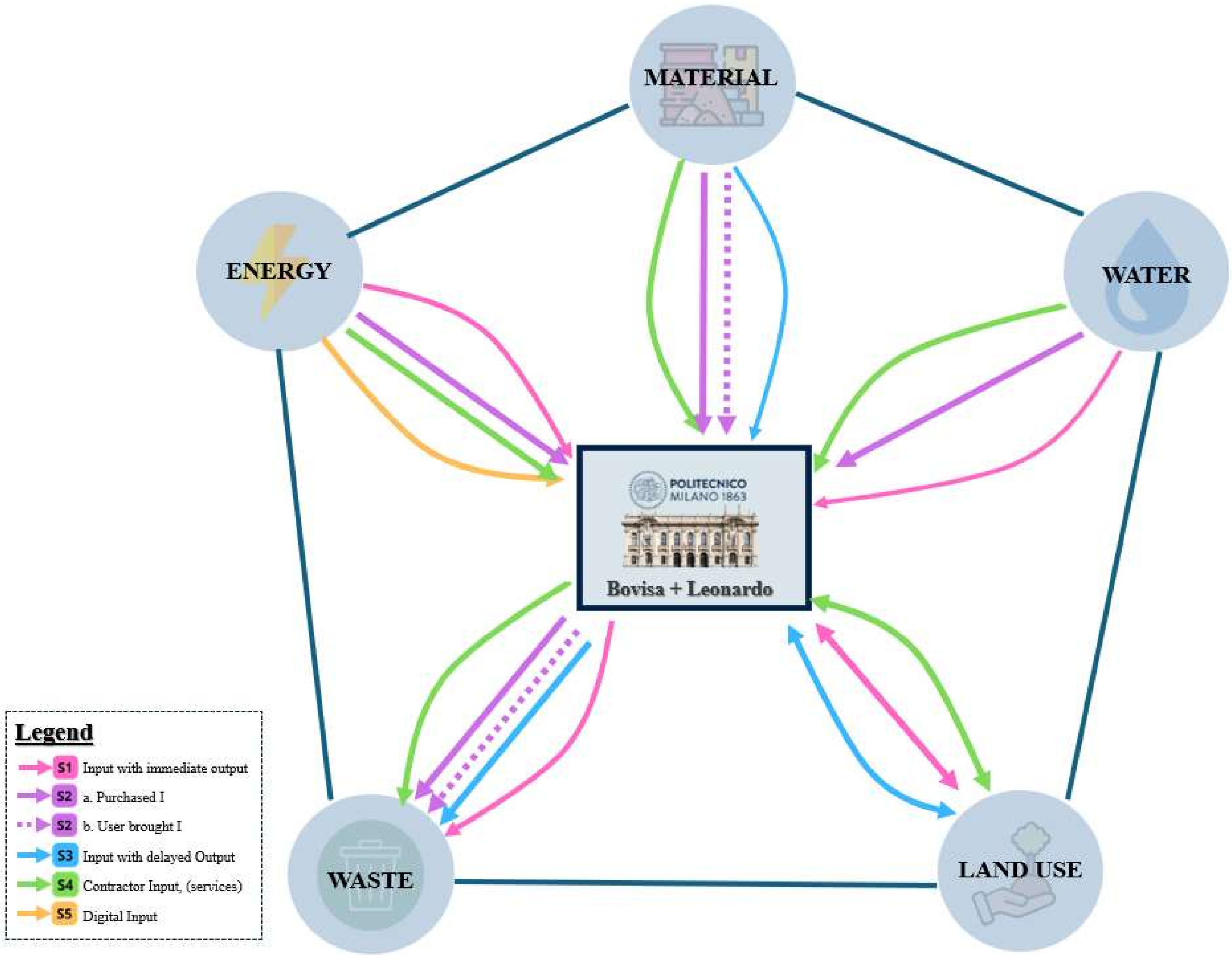

Figure 2.1: Radial Diagram.

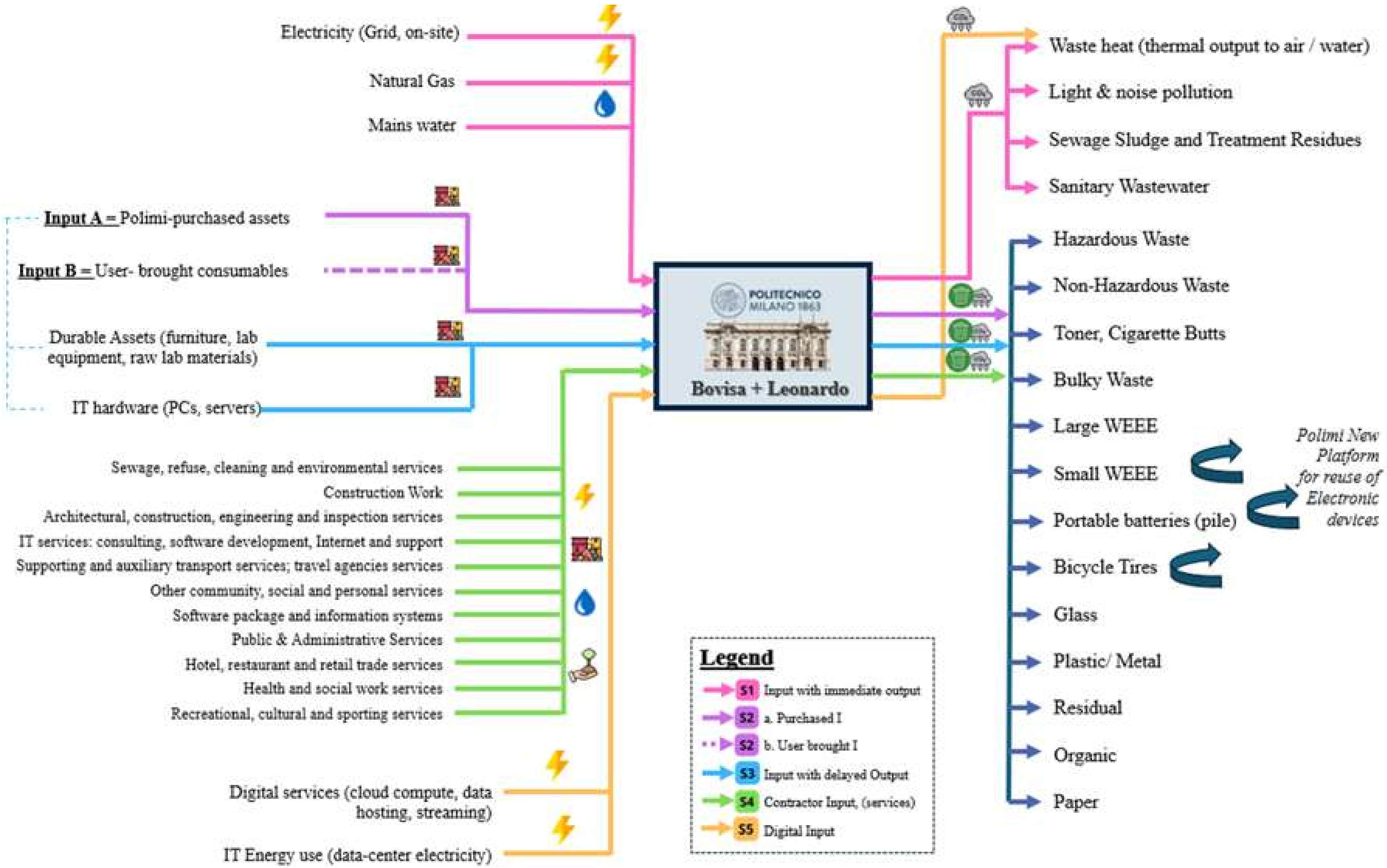

Figure 2.2: Input-Output Diagram.

Table 2.2: Concept - Stream Link.

Concept	Linked Streams	Explanation for Linking
1. ENERGY	S1, S2a, S4, S5	• S1 (Immediate direct inputs/outputs): Direct energy consumption within POLIMI operations (electricity, heating, cooling). • S2a (POLIMI purchases): Embedded energy in purchased goods (consumables, food, banners). • S4 (Outsourced services): Energy used by contracted services (cleaning, catering, maintenance). • S5 (Digital services): Energy used by intangible services (cloud computing, streaming), mainly emissions.
2. WATER	S1, S2a, S4	• S1: Direct water consumption and wastewater generation on-site. • S2a: Water embedded in purchased goods and consumables. • S4: Water use associated with outsourced services (cleaning, catering, maintenance) and related wastewater outputs.
3. MATERIAL	S2a, S2b, S3, S4	• S2a (POLIMI purchases): Consumables, office supplies, food, banners. • S2b (User-brought): Materials brought by users (e.g., student food waste). • S3 (Capital goods): Long-lived assets like furniture, electronics amortized over time. • S4 (Outsourced services): Materials used in contracted activities (cleaning products, construction materials, printing cartridges).

Concept	Linked Streams	Explanation for Linking
4. WASTE	S1, S2a, S2b, S3, S4	• S1: Immediate waste streams generated on-site (wastewater, operational waste). • S2a: Waste from consumables after short use. • S2b: Waste generated by users. • S3: Disposal of capital goods at end-of-life. • S4: Waste resulting from outsourced services (empty cleaning bottles, construction debris, printing waste).
5. LAND	S4, S3, S1	• S4: Outsourced maintenance, construction and landscaping services are the primary activities that physically transform the campus grounds and its ecological characteristics. • S3: Capital goods such as furniture, laboratory equipment and IT infrastructure occupy physical campus space for extended periods, contributing to how built areas are used and densified over time. • S1: Direct water intake or discharge and energy-related externalities occur within the physical campus footprint, impacting the local biodiversity of the areas being actively used.

The following section defines which of these Concept-Stream combinations fall within the active scope of this thesis and why.

2.5. Operational Perimeter

Having defined the classification logic used to organize POLIMI's flows, the natural next step is to decide where exactly this thesis operates and applies. Although this work does not conduct a full O-LCA, the established Operational Perimeter that follows was structured around the same boundary principles that organizational environmental assessments require. The intersection of these boundary decisions determined what fell inside and outside the scope of this work.

Any organizational inventory should begin by specifying the physical area under assessment, and for this thesis that space was represented by Leonardo and Bovisa Campuses, which constitute POLIMI's operational core. This choice aligned with the ISO/TS 14072 definition of operational control, which requires, as also explained in the Stream Logic, that the assessed units be those where the organization holds the authority to introduce and implement operating policies [30].

Then, aligned with the geographical boundary, the second boundary defined the position of the thesis within the value chain of the university, adopting an LCA "gate-to-gate" perspective [30]. This means that the subsequent work is focused on what materials arrive on campus (gate in) and which waste is collected and leaves POLIMI's physical control (gate out). Gate-to-gate was adopted because it corresponds to the segment of the value chain where POLIMI has direct data access and where flows are practically traceable; in contrast, upstream manufacturing or downstream waste treatment are activities carried out by external operators.

The third boundary concerned the environmental scope of the thesis, which was limited to the Concepts of Material and Waste as they represent the two sides of the "same" physical flow when analysing what enters and leaves the system. This focus is further supported by Schiavon et al. [31], who show that waste-related data in HEIs is often incomplete or inconsistently reported, therefore frequently excluded from research, while data related to energy and water are the most frequently reported. In this context, the inclusion of Material becomes necessary and logical as it constitutes the physical inputs that ultimately generate the Waste and allows the study to trace the input-output relationship within the defined perimeter. Energy, Water, and Land, although valid Concepts within the broader framework, represent independent environmental domains that do not participate in the analysed relationship and require distinct analytical approaches that fall outside the scope of this thesis.

Applying these three boundaries together determines which flows fall within the active scope of this thesis.

- Included: S2a, S3 and S4, which represent material flows purchased or contracted by POLIMI within the gate-to-gate boundary. S4 was included in principle, as outsourced services generate physical waste within the boundaries. However, due to the high heterogeneity of service-related procurement data, the decision to include or exclude specific coded rows was made individually for each waste stream. The detailed reasoning and resulting data coverage are discussed further in Chapter 5.

- Excluded: S1 because it covers Energy and Water, which fall outside environmental scope; S2b due to the fact that it originates from external users outside POLIMI's operational control; and S5 digital services as it falls outside the gate-to-gate material flow logic for this work.

Lastly, while not a boundary per se, the temporal scope was initially set to cover 2020-2024, as procurement data allowed for a multi-year analysis. However, waste data availability was more fragmented, covering primarily 2023 and 2024 with partial extensions to 2025 for specific waste types, as will be detailed in the following chapter. Therefore, the temporal coverage varies by data source rather than following a single unified period.

With the analytical boundaries established, the following section describes how data was collected within them.

2.6. Data collection strategy: hybrid approach

This thesis drew on two data sources: procurement records from POLIMI's administrative systems and three waste-measurement datasets collected from campus operations.

On one hand, the procurement records were provided by POLIMI's Procurement Department upon request, drawn from the *Banca Nazionale dei Contratti Pubblici* (*BDNCP*), the national public procurement registry managed by ANAC *(Autorità Nazionale Anticorruzione)*, to which all Italian public institutions are legally required to report their contracts. While the underlying registry is publicly accessible, the specific file used here (acquisti_POLIMI_13_25_CPV.xlsx) was given directly by the procurement team, who had enhanced it internally, making it a custom file rather than a standard public download. On the other hand, the three sources referenced throughout this thesis were closer to administrative reports than to datasets in the analytical sense. These documents were provided on request by the Waste Management Department, with each being compiled as a separate administrative report shared with the research team rather than through direct database access. More information on these is provided in Appendix A.3.

Together, these sources formed a hybrid data collection strategy that combined top-down procurement analysis with bottom-up waste measurement [15], consistent with the recommendation of UNEP's organizational life cycle guidance. To implement this hybrid approach, the thesis applied the Data Acumen framework proposed by Pereira et al. (2025), which provides a diagnostic tool for assessing data maturity along a practicality spectrum and for selecting digital tools that match the complexity and reliability of each data stream [32].

Based on this diagnostic evaluation, all data used in the study was primary data drawn directly from POLIMI's own operations, representing the foreground system of the inventory. On one hand, procurement records were classified as theoretical data, since they required non-empirical methods such as clustering and monetary-to-mass conversions to estimate physical quantities. To maintain a low financial cost but high manual effort workflow, these tasks were performed using Python. On the other hand, waste datasets were classified as practical data, as they consisted of direct operational measurements and were consolidated using standard spreadsheets, which are low-cost and appropriate for medium-effort manual processing. Additionally, artificial intelligence semantic tools were employed to process the unstructured procurement descriptions in two analytical instances. In one instance, the tools supported the linking phase by semantically matching procurement inputs to the appropriate physical waste output types studied. In another instance, they assisted the clustering phase by interpreting the raw text from the data to help group individual purchasing records into coherent material categories.

Both applications relied on the raw text extracted from the procurement description fields in the dataset. To enhance the reliability of these semantic interpretations, about four different artificial intelligence models were utilized to cross-verify outputs. By conducting random evaluations where one model audited the results proposed by another, the study introduced an additional layer of validation. Finally, across all automated processes, the models were also required to flag ambiguous entries for manual verification, ensuring that the researcher maintained methodological control and rigour throughout the analysis.

This combined strategy ensured that both the input and output sides of the material flow were systematically captured while remaining feasible within the university's current data infrastructure. It is important to highlight that the initial methodological assumption of this study was to use procurement records as the primary anchor for material quantification. However, as the research progressed, the inherent characteristics of CPV (Common Procurement Vocabulary, the EU standard classification system for public procurement) coding, including variable granularity and the co-occurrence of service and goods entries within single records (detailed in Chapter 4), rendered a direct monetary-to-mass conversion unfeasible as a starting point. Consequently, the analytical approach was adjusted to instead anchor the empirical work in measured waste outputs, which served as the stable reference point. Hence, procurement data was used as a secondary supporting dataset, mapped against the Waste Typology to test its validity as a proxy for material inflows.

The following chapter presents the first of these two outcomes: the Waste Typology constructed from the three raw waste measurement sources.

3 Results I: Waste Typology Construction

3.1. The 3 raw datasets and their structure

The output side of the material flow was represented by the waste. In order to establish a reference against which the input side could later be compared, information regarding quantification of waste streams was requested from different departments. As described in Section 2.6, the three sources were obtained directly from POLIMI's Waste Management Department as internal operational reports. The three primary sources obtained were Excel files that were not datasets in the analytical sense, but semi-manual reporting sheets combining measured values, estimates, comments and assumptions in non-standardized formats. The first data source was the most internally organized, where only recorded weights seemed to be present, covering approximately six months (July to December) of 2024 and including all the waste type names and the collection channels. The second one presented information regarding the Special Waste from 2023 and Urban Waste from 2024. And the third data source showed partial information from Special Waste of 2024 with more granular data from a "sampling campaign" on Paper Waste of 2025 divided by collection point on the targeted Campuses (Bovisa and Leonardo).

Although each document broadly describes the same waste system, they do so using different boundaries, different measurement logics and different assumptions. When integration of the three sources was attempted, these differences brought to light the existence of structural contradictions that prevented direct integration. Summarized below are the main inconsistencies found within them.

- Spatial heterogeneity: Each data source adopts a different Operational Perimeter. For example, the numbers reported in one document refer to values including weighted waste from the territorial campuses (Territorial Poles), while in the other document the presented values did not include them, which complicated the distinction of which numbers to consider according to the included Streams established in the previous chapter.
- Temporal heterogeneity: The same reported values appear across sources with different time references attached to them, making the conversion to yearly

values unclear. This instability has been present for years. A similar situation occurred in 2014, when records for the Bovisa campus similarly required estimation because paper and urban waste data were only available from June onwards [33].

- Typological heterogeneity: For the same campus and waste type, the three sources in many cases report different container types, which made it unclear whether datasets described the same Stream or different ones.
- Data completeness heterogeneity: Streams appear in one source and disappear in another, with no clarity on whether the absence reflects zero, aggregation, omission or simply not reporting.

Overall, the three raw data sources are not contradictory in isolation; they become contradictory when placed next to each other, demonstrating that these inconsistencies are structural. They reflect the absence of a shared classification system that could later also facilitate the collection of data, making a unified typology not only useful but necessary.

3.2. Waste Typology

As previously explained, at first glance, merging the information seemed the most logical path to follow; nonetheless, the available data was created for operational reporting, not for analytical integration, and therefore lacked a shared structure. Hence, instead of attempting to reconcile formats that were never designed to align directly, the thesis organized the waste data into a classification structure grounded in Italian regulatory definitions and POLIMI's operational practices. As a secondary benefit, this structure is documented in a form that could allow the university to collect waste-related data much faster in the future, while still staying fully aligned with legal requirements and institutional regulations.

The typology developed for this study is grounded in the legal definitions governing waste management in Italy, primarily D. Lgs. 152/2006 (Environmental Consolidated Act). The principal distinction between municipal and special waste follows this Act, as amended by D. Lgs. 116/2020, which redefined "urban waste" to include non-domestic waste similar in nature to domestic waste [34], meaning that universities like POLIMI are treated like schools for waste purposes [35], allowing them to hire private recyclers instead of the city, provided the university supplies proof of recycling.

Hazardous criteria within the Waste Typology are derived from the classification requirements of D. Lgs. 152/2006, utilizing European Waste Codes (CER) to identify waste origin, typology of the activity that generated it and hazardous characteristics (HP codes). Documentation and traceability for special wastes are managed through mandatory identification forms and registers as required by national law [36].

Just as the proposed typology is legally grounded, it is also fully aligned with the organizational classification established by the *Rete delle Università per lo Sviluppo Sostenibile (RUS)*, which considers POLIMI as a hybrid model that combines traits of multi-site and campus-based institutions, accounting for geographical diversity and the integration of diverse academic disciplines across decentralized structures [35].

The Waste Typology is organized in two macro groups reflecting both the regulatory distinctions described above and the way waste is operationally handled at POLIMI. The first macro group, Municipal, covers the municipal fractions collected through AMSA, Milan's municipal waste management company, which follow the standard urban domestic-like categories (paper, plastic/metal, glass, organic and residual) used across the city and are reported through cumulative weights. AMSA weight values are often estimated based on container volume or citywide averages, which limits the suitability of these data for detailed attribution work. Thus, the typology treats this macro group as a single, externally managed one that is analytically distinct.

The second macro group, Special, brings together all streams that require dedicated handling, private contracts or internal tracking systems. This macro group reflects the factory-like component of the system and is organized into two management channels that correspond to how waste is physically collected and documented. *Appalto*, the first channel, includes large WEEE, bulky items, hazardous laboratory waste, non-hazardous laboratory waste, toner and cigarette butts. These streams are managed through scheduled pick-ups, FIR forms, loading registers or contractor-specific recovery systems. *Convenzione*, the second channel, includes small WEEE, batteries and bicycle-related flows generated by the campus population. These streams are collected through consortium agreements or dedicated campus initiatives and are documented through consortium reports or convention logs.

Unlike the fragmented lists and information found in the original sheets, the resulting classification reflects how waste is actually generated, collected and documented across the university, and proves capable of accommodating the diversity of waste streams encountered in the analysis.

Several fractions in the typology originate from more than one Stream. To maintain analytical clarity, each is assigned a primary origin stream, with secondary inputs noted when relevant. Municipal fractions combine S2a and S2b inputs, since AMSA's aggregated reporting does not allow these to be separated. Small WEEE and Batteries are mainly S2b, with a smaller S2a component from institutional devices. Cigarette butts and bicycle tires are classified as S2b because they are generated by the campus population, although their removal is managed through service agreements. These overlaps reflect the attribution complexity that the Stream Logic tries to capture.

The Waste Typology, better explained in Table 3.1, incorporates a set of operational rules that translate the structural categories into consistent classification criteria. WEEE are assigned to *Appalto* or *Convenzione* based on a physical size filter, reflecting actual collection practices and supporting the thesis Stream Logic where mainly Small WEEE is linked to S2b (User-brought material) and Large WEEE to S3 (Long-term POLIMI purchases).

Hazardous identification follows the HP criteria of Annex I of D. Lgs. 152/2006, ensuring that lithium batteries, toner with hazardous components and laboratory reagents are correctly flagged, while alkaline batteries and bulky items remain non-hazardous.

Likewise, traceability requirements also define how Special Waste is recorded. Large WEEE and bulky items rely on FIR forms, laboratory waste on loading and unloading registers, and toner, batteries and bicycle-related flows on contractor or consortium documentation.

Table 3.1: The Waste Typology.

Macro-Category	Management Channel	Frazione (Typology)	Thesis Stream Linnk	PoliMi Specifics & Item Descriptions	Hazard Level	IDEAL Data Source	Year	Container Typology	Quantity Column	Unit	Status (Measured / Estimated / Not	Source	Notes
MUNICIPAL	AMSA (Comune)	Paper (Carta)		Newspapers, magazines, clean pizza boxes, tetrapack. NO receipts or greaseproof paper.	Non-Haz	AMSA cumulative weights	2024	Wheeled bin (Carrellato)	-	kg	*Not Available*	-	Using a merge of the 3 Sources.
								Container (Contenitore)	46.860,00	kg	Measured	Source #1: Tabella rev 3_1	
							2025	Wheeled bin (Carrellato)	74.602,67	kg	Measured	Source #3: Emails 7 august + 16 december	
								Container (Contenitore)	-	kg	*Not Available*	-	
		Glass (Vetro)	Primary: S2a (short-term Polimi purchased)	Bottles and jars without lids.	Non-Haz	AMSA cumulative weights	2024	-	-	kg	Read note	Source #1: Tabella rev 3_1	3,276 kg for Leonardo, not information from Bovisa.
		Plastic/Metal (Plastica/Metallo)	Secondary: S2b (user-brough items)	Containers, plates, bottles, cans, polystyrene, film, caps.	Non-Haz	AMSA cumulative weights	2024	Contenitore 20 mc	39.360,00	kg	Estimated	Source #1: Tabella rev 3_1 Source #2: Rifiuti Urbani prod 2024	Unclear timeframe, chosen highest estimation
		Residual (Indifferenziato)		Residual: Nappies, x-rays, dirty paper, ceramic, receipts.	Non-Haz	AMSA cumulative weights	2024	Electric Compactor (Compattatore elettrico) 20 m³ + Container (Contenitore) 1,1 m³	252.330,00	kg	Estimated	Source #1: Tabella rev 3_1 Source #2: Rifiuti Urbani prod 2024	The highest between Source #1 and #2 was chosen.
		Organic (Organico)	S2a + S2b + S4 (generated through outsourced services)	Food scraps, coffee grounds, napkins, flowers.	Non-Haz	AMSA cumulative weights	-	-	-	-	*Not Available*	-	Data Source #1 comment= "Da estimare - dato dei concessionari di ristorazione"
SPECIAL	APPALTO	Large WEEE (RAEE)	S3 (long-life Polimi purchased)	Physical Filter: Items > bin size (Fridges, Monitors, UPS). Split into Admin (ASICT) vs. Scientific.	Haz*/Non-Haz	FIR Forms / ASICT Inventory	2024	Baskets + loose waste (Ceste + Sfuso)	54.255,00	kg	Measured	Source #1: Tabella rev 3_1	Only included Campuses (from Source #1)
		Bulky (Ingombranti)		Furniture, fittings, models. Replaced for safety/fire norms, not just wear.	Non-Haz	FIR Forms	2024	Container (Contenitore)	116.935,00	kg	Measured	Source #1: Tabella rev 3_1	Only included Campuses (from Source #1)
		Hazardous (Pericolosi)	Primary: S2a (short-term Polimi purchased)	Hazardous: Lab reagents, PPE (DPI), Neon.	Hazardous (*)	Loading Registers	2024	Jerrycans (taniche), drums (bidoni), big bags (big bag), cardboard boxes (Scatola)	29.044,00	kg	Measured	Source #1: Tabella rev 3_1 Source #3: Emails 7 august + 16 december	Only included Campuses (from Source #1)
		Non Hazardous (Non Pericolosi)	Secondary: S4 (generated thorugh outsourced services)	Metals, wood, inert materials, inorganic chemicals.	Non-Haz	Loading Registers	2024	Jerrycans (taniche), drums (bidoni), big bags (big bag), caged baskets (ceste gabbiate)	287.404,00	kg	Measured	Source #1: Tabella rev 3_1	Only included Campuses (from Source #1)
		Toner (Consumabili da stampa)	S4 (generated through outsourced services)	Printing consumables. Managed via specialized recovery contracts.	Hazardous (*)	Contractor Logs	-		-		*Not Available*	-	Insufficient data
		Cigarette Buts (Mozziconi)	Secondary: S2b (user-brough items)	Cigarette butts (dedicated sustainability flow).	Non-Haz	Contractor Logs	-		-		*Not Available*	-	Insufficient data
		Small WEEE (Piccoli RAEE)	Primary: S2b (user-brough items)	Physical Filter: Fits bin (phones, mice, pc, music players).	Non-Haz	Consortium Reports	-		-		*Not Available*	-	Insufficient data
	CONVENZIONE	Batteries (Pile)	Secondary: S2a (short-term Polimi purchased)	Separate from RAEE. Split: Lithium vs. Alkaline.	Haz* (Lithium) / Non Haz (Alkaline)	Consortium Reports	-		-		*Not Available*	-	Insufficient data
		Bicycle Tires (Copertoni Bici)	S2b (user-brought items)	Inner tubes and used bicycle tires (campus population).	Non-Haz	Convention Logs	-		-		*Not Available*	-	Insufficient data

The separation of wastes within this typology, beyond providing a classification structure, also reflects the underlying traceability of each stream, which directly conditions the reliability of the subsequent procurement-to-waste comparison carried out in Chapter 5. AMSA's data offers low traceability, since municipal data is generally aggregated across all households within a specific zone. Fortunately, for this project, AMSA began providing weight-based data only recently and exclusively for paper, following a specific request from the university that allowed estimations and approximations for the quantification in the next section. By contrast, the *Appalto* channel offers high precision as it is legally documented information through FIR forms, laboratory registers and ICT inventories, making it the most reliable component for the matching. This reliability is further supported by the internal checks carried out by POLIMI's Sustainability Service, which reviews FIR documentation to confirm the consistency of reported quantities [25]. In the middle, the *Convenzione* channel captures decentralized population-driven flows such as small WEEE and batteries, documented through consortium or convention reports rather than institutional systems.

In this sense, beyond its role in this analysis, the typology produced here could also support POLIMI's future data collection efforts, as the Data Source column in Table 3.1 could serve as a direct operational guide indicating where each waste stream's data should be retrieved in any updates or extensions of this analysis.

3.3. Quantification of Waste Sub-concepts

Table 3.2 presents the consolidated quantities, where possible, for the fourteen waste fractions considered in this study, grouped by management channel as explained in the previous section. For each stream, the table reports the annual quantity in kilograms, the reference year, and the status of the value (Measured, Estimated - Conversion, or Not Available). The purpose of this section is to clarify the methodological assumptions behind the estimated values and to highlight the main data limitations.

For AMSA-managed fractions, paper was the only fraction for which a complete estimation was possible, since for the purposes of this project, POLIMI requested dedicated measurements of its paper waste starting in July 2025. AMSA collects waste at the zone level, so POLIMI's waste could not be distinguished from that of nearby buildings. Thus, the sampling carried out provided a more accurate density value for paper that was applied in the estimation. This estimation combines (i) campus infrastructure data containing the number of wheeled bins ('*carrellati*') and containers, and measured container flows from July to December 2024; (ii) other measured container flows from July to October 2024; and (iii) sampling campaign data from 2025 (*carrellati*). These three sources were harmonized using the frequency from Source (ii) and the densities from Source (i), resulting in a total annual estimate of 121.462,67 kilograms for 2024 and 2025 combined.

For glass, no complete measured data existed for 2024 across the datasets. A partial estimate was obtained using Source (i), which reported 39 wheeled bins of 240L each at the Leonardo Campus. Converting this volume to mass using the institutional benchmark density of 350 kilograms/m^3 presented in POLIMI's Waste Report of 2016 [25], yielded 3.276 kilograms. Because Bovisa container data were missing, this incomplete estimate was not included in the consolidated tables.

For Plastic/Metal and Residual fractions, the estimation required choosing between Source (i) and Source (ii). Each provided data for different time periods, so both were first converted to yearly averages to ensure comparability and later the higher estimate of the two values was selected as the reference, following a conservative logic that assumed that in the context of an environmental inventory, overestimating waste generation is preferable to underestimating it, as the latter would risk obscuring potentially relevant environmental flows.

Organic waste remained unavailable as the main source containing this stream noted that the value had to be "estimated by food-service concessionaires".

For *Appalto*-managed special waste, quantities reported in the table were taken mainly from Source (iii), which corroborated many values reported in Source (ii). Values were complete for some streams but remained absent for others.

Lastly, for *Convenzione*-managed fractions, despite information in Source (i) about the container type where they are collected, no quantitative data was available.

Overall, the quantification process required the integration of measured data where available, and the application of transparent, defensible estimation methods where direct measurement was not possible. The Status column in Table 3.1 explicitly distinguishes between measured and estimated values to preserve methodological clarity.

Table 3.2: Waste Numerical Results.

Typology (Frazione)	Year	Tipologia	Quantity	Unit
Paper (Carta)	2024	Wheeled bin (Carrellato)	-	
		Container (Contenitore)	46.860,00	
	2025	Wheeled bin (Carrellato)	74.602,67	
		Container (Contenitore)	-	
Glass (Vetro)		*Not available*		
Plastic/Metal (Plastica/Metallo)	2024	Container (Contenitore) 20m³	39.360,00	kg
Residual (Indifferenziato)	2024	Electric Compactor (Compattatore elettrico) 20 m³ + Container (Contenitore) 1,1 m³	252.330,00	
Organic (Organico)		*Not available*		
Large WEEE (RAEE)	2024	Baskets + loose waste (Ceste + Sfuso)	54.255,00	
Bulky (Ingombranti)	2024	Container (Contenitore)	116.935,00	
Hazardous (Pericolosi)	2024	Jerrycans (taniche), drums (bidoni), big bags (big bag), cardboard boxes (Scatola)	29.044,00	
Non Hazardous (Non Pericolosi)	2024	Jerrycans (taniche), drums (bidoni), big bags (big bag), caged baskets (ceste gabbiate)	287.404,00	kg
Toner (Consumabili da stampa)		*Not available*		
Cigarette Buts (Mozziconi)		*Not available*		
Small WEEE (Piccoli RAEE)		*Not available*		
Batteries (Pile)		*Not available*		
Bicycle Tires (Copertoni Bici)		*Not available*		

3.4. Prioritization of Sub-concepts

As established in the preceding sections, POLIMI is a complex institution that manages a wide range of heterogeneous waste streams. For the scope of this thesis, the analysis of all the fourteen types with equal depth would have been neither feasible nor methodologically sound. Therefore, a structured prioritization was necessary to determine where to focus the subsequent empirical analysis. While it is true that physical quantity is one relevant dimension, there are other factors that need to be taken into consideration to better understand where to focus the effort and ensure transparent decisions.

UNEP guidelines explicitly encourage this approach in its Section 3.2, which underscores that organizations should “focus on the most relevant activities” and introduces the concept of cut-off to exclude less significant flows [15]. This source includes a table outlining various criteria, which directly serve as the theoretical backbone for the drivers used in the matrix. Table 3.3 below illustrates the six drivers considered for the matrix with their explanation and link to the criteria from the O-LCA guidelines and the assigned weights.

Weights on the table reflect the priorities of the study. As noted in the ILCD Handbook, any weighting set inherently involves value choices and the O-LCA guidelines do not prescribe weights, confirming that they must be adapted to the study’s goals. Accordingly, the weights assigned across all six drivers were defined to align with the research objectives and were shaped by information shared during the meetings with the Waste Management and Procurement Departments. The assignment reflected two priorities inherent to this research: (i) the methodological focus on procurement data traceability as the empirical core of the thesis, which justifies its elevated weight of 30%; and (ii) the institutional context of the university, where environmental impact and stakeholder visibility carry greater strategic relevance than in industrial settings. The remaining drivers were assigned moderate weights based on their relative importance in the university management context, in alignment with the study’s goal.

Table 3.3: Prioritization Matrix Drivers.

Driver	Detailed Explanation	Link to O-LCA Guidelines Table	Weight
1. Waste Stream Volume	Measures the physical quantity of waste generated by each stream. Higher volumes indicate a larger absolute environmental burden and greater operational relevance. This driver captures the scale of the flow entering the system boundary.	Directly corresponds to quantitative criterion "Mass or energy: contribute significantly to the total mass or energy flow” [15].	15%
2. Environmental Impact	Evaluates the inherent environmental burden of each stream across its life cycle, including toxicity, carbon intensity, and end-of-life treatment, representing the potential harm to ecosystems,	Direct match with the criterion "Environmental impacts: contribute significantly to the total anticipated resource use and emissions” [15].	20%

Driver	Detailed Explanation	Link to O-LCA Guidelines Table	Weight
	human health, or climate, therefore capturing environmental significance independent of volume.		
3. Waste Hierarchy Position	Evaluates the realistic potential for improving the management of each waste stream within the EU waste hierarchy. Streams that can be shifted toward prevention or reuse receive higher scores because they offer greater opportunities for upstream reduction.	Strong match with organizational criterion "Influence: present potential emissions reductions that could be undertaken or influenced by the reporting organization" [15]. The hierarchy position reflects the organization's ability to influence outcomes.	10%
4. Health and Safety Risk	Measures the hazard severity associated with handling or exposure to waste.	Direct match with the organizational criterion "Risk: contribute to the risk exposure of the reporting organization, including regulatory, compliance, and safety risks" [15].	10%
5. Stakeholder and Community Impact	Captures the visibility of the waste stream to the university community and its relevance to stakeholders such as students, staff, suppliers, and civil society. Streams deemed critical by key stakeholders score higher, reflecting institutional reputation and engagement potential.	Direct match with the organizational criterion "Stakeholders: deemed critical by key stakeholders" [15].	15%

Driver	Detailed Explanation	Link to O-LCA Guidelines Table	Weight
6. Procurement Data Traceability	Measures how reliably each waste stream can be linked to procurement records through CPV codes. This is a methodological driver specific to the thesis, and it captures data availability and methodological feasibility.	No direct equivalent in the guidelines' table, but it is intentionally added as a criterion specific for the thesis.	30%

The allocation of points within the prioritization matrix followed a consistent and simple rule. For each driver, only the top five waste streams received points. The highest-ranking stream was assigned five points, the next four, and so on until the fifth position, which received one point. All remaining streams received zero points. Tied streams were assigned equal point values, preserving the integrity of the ranking while avoiding arbitrary distinctions. This approach allowed the matrix to highlight meaningful differences without artificially inflating the importance of lower-ranking streams.

The resulting tables present first in Table 3.4 the raw scores assigned to each stream across the six drivers, and then in Table 3.5 the corresponding weighted scores obtained by multiplying each raw score by the weight of the driver, displaying the total weighted score for each stream and the resulting ranking.

The outcome of this process was straightforward. The highlighted streams in green (Paper and Large WEEE) represented the highest-scoring group and therefore constituted the priority set for the next chapter, while the yellow-highlighted ones (Bulky and Special Hazardous Waste) constituted the secondary priority that still merited further examination.

Table 3.4: Prioritization Matrix Weight Assignment.

Driver	Waste Type / Weight	Paper (Carta)	Glass (Vetro)	Plastic/ Metal (Plastica/ Metallo)	Residual (Indifferenziato)	Organic (Organico)	Large WEEE (RAEE)	Bulky (Ingombranti)	Hazardous (Pericolosi)	Non Hazardous (Non Pericolosi)	Toner (Consumabili da stampa)	Cigarette Butts (Mozziconi)	Small WEEE (Piccoli RAEE)	Batteries (Pile)	Bicycle Tires (Copertoni Bici)
Waste Stream Volume Potential	15,00%	3			4		5	2		1					
Environmental Impact	20,00%				3		4	2	5					1	
Waste Hierarchy Position	10,00%	5		2		3	4				1		4		
Health & Safety Risk	10,00%				1		4		5				3	2	
Procurement Traceability Potential	30,00%	5					3	4	2		1				
Stakeholder/ Community Impact	15,00%	4		5	1		3	2			1		3		
	100,00%														

Table 3.5: Prioritization Matrix Result.

Driver	Waste Type / Weight	Paper (Carta)	Glass (Vetro)	Plastic/ Metal (Plastica/ Metallo)	Residual (Indifferenziato)	Organic (Organico)	Large WEEE (RAEE)	Bulky (Ingombranti)	Hazardous (Pericolosi)	Non Hazardous (Non Pericolosi)	Toner (Consumabili da stampa)	Cigarette Butts (Mozziconi)	Small WEEE (Piccoli RAEE)	Batteries (Pile)	Bicycle Tires (Copertoni Bici)
Waste Stream Volume	15,00%	0,45	0	0	0,6	0	0,75	0,3	0	0,15	0	0	0	0	0
Potential Environmental Impact	20,00%	0	0	0	0,6	0	0,8	0,4	1	0	0	0	0	0,2	0
Waste Hierarchy Position	10,00%	0,5	0	0,2	0	0,3	0,4	0	0	0	0,1	0	0,4	0	0
Health & Safety Risk	10,00%	0	0	0	0,1	0	0,4	0	0,5	0	0	0	0,3	0,2	0
Procurement Traceability	30,00%	1,5	0	0	0	0	0,9	1,2	0,6	0	0,3	0	0	0	0
Potential Stakeholder/ Co-mmunity	15,00%	0,6	0	0,75	0,15	0	0,45	0,3	0	0	0,15	0	0,45	0	0
	100,00%														
	TOTAL	3,05	0	0,95	1,45	0,3	3,7	2,2	2,1	0,15	0,55	0	1,15	0,4	0
	POSITION	2					1	3	4						

4 Results II: Procurement Dataset Restructuring

4.1. CPV Dataset Structure: Characteristics and implications.

As mentioned in Section 2.6, while the raw CIG (*Codice Identificativo Gara*) registry is publicly accessible at dati.anticorruzione.it, the procurement export employed throughout the analysis was a custom file prepared internally by POLIMI's Procurement Department, refined specifically for this analysis, hence not a routine public download.

Each record in the file corresponds to a contract lot. The raw dataset contains numerous administrative, financial and classification fields. For the initial scan of the data, attention was placed on a small set of core variables, specifically: the unique contract identifier (*CIG*), text descriptions of the lot and the overall tender (*oggetto_lotto* and *oggetto_gara*), the awarded monetary value at both lot and tender level, the responsible cost centre (*denominazione_centro_costo)*, the year and month of award (*anno, mese*), and the CPV code with its associated label (*cod_cpv, descrizione_cpv*). These provided the basis for the early quality and structure checks, before the column set was later narrowed during the harmonization steps. The characteristics and reliability implications of the CPV coding are discussed in the following section.

The Common Procurement Vocabulary (CPV) is the European Union's standard classification system for public procurement that classifies goods and services. Its structure is hierarchical: broad 2-digit divisions, 3-digit groups, 4-digit classes, 5-digit categories, and 6 to 8-digit levels displaying more granularity where needed [37]. In an ideal procurement dataset, each item carries an 8-digit code that cleanly reflects its position within this hierarchy, allowing consistent monetary aggregation and interpretation.

The dataset received from the Procurement Department contained 97.642 records and covered purchases dating back to 2013. It included CPV codes, monetary values and some descriptive text fields. For purchases above approximately 40.000 euros, CPV codes were assigned manually by procurement staff, while purchases below this threshold were coded by an AI-based prediction system trained on those same human-coded records. At first glance, it appeared to be a suitable foundation for the reconstruction of material inflows. A closer inspection, however, revealed that several characteristics of the dataset required methodological accommodation before it could be used for environmental mapping purposes. First, many 8-digit subcodes carried higher monetary values than their 3-digit parent groups, reflecting the fact that CPV codes were assigned at the procurement lot level rather than per item, which created a natural mismatch with the CPV hierarchy when individual items were considered.

A second characteristic of the dataset was the presence of service codes within the "Supply (*Fornitura*)" category, which reflected the common practice of bundling goods and services within the same procurement contract. Even after filtering the dataset to include only supplies, several rows still carried CPV codes that clearly belonged to service categories. This indicates that goods and services were frequently mixed within the same procurement process, making it impossible to rely purely on CPV codes for the identification of material purchases. Third, the use of 2-digit division codes, while sufficient for high-level administrative tracking, prevented any meaningful identification of the material category and subsequent link to a waste type as they were too broad.

The fourth characteristic concerned records with missing or invalid CPV codes. Within the dataset, 3.677 rows either lacked a valid code (recorded as 99999999) or did not include a description. These belonged to a broader group of 10.737 manually inserted entries, identifiable through the SmartCIG column, which were naturally prone to inconsistencies. These entries were labelled as DC (Double Check) and excluded from the analysis. The remaining 7.060 manually inserted entries contained valid identifiers and were retained. This approach did not affect the robustness of the analysis, as the DC rows represented less than 5% of both total records and associated expenditure. After the removal, the dataset used for initial analysis consisted of 93.965 records.

Taken together, these characteristics reflect that the dataset was designed and maintained for administrative procurement management, not for environmental inventory, making it impossible to use the raw dataset as a basis for the later analysis. The CPV structure was too fragmented to aggregate purchases by material type, and the presence of missing or non-standard codes made reliable classification unfeasible. The mixed use of manual and AI-based coding further meant that classification reliability could not be assumed to be uniform across records. In this regard, a full reclassification of CPV codes was therefore required before any procurement-to-waste mapping could be attempted.

4.2. The reclassification process

Following the quality check described in the preceding section, which reduced the dataset to 93.965 records, the dataset was narrowed to match the Operational Perimeter established in previous chapters by applying three main filters: a 2020 to 2024 temporal window, a geographic focus by excluding records labelled as POLIMI's territorial campuses, and a category restriction to "*Fornitura*" in order to isolate physical material supplies from intangible services or construction works. By doing so, the dataset was reduced to 19.457 records, representing about 21% of the original size, which is consistent with the fact that the raw data spans more than a decade.

With the dataset scoped, a further decision concerned the level of the CPV hierarchy at which to aggregate purchases in order to address the problems described in the previous section. The choice to keep them at a 3-digit CPV group level was methodological and not arbitrary.

It was mainly founded in the principle of cognitive economy, by which classification systems "…aim to convey 'the maximum information with the minimum cognitive effort' [38]." In a taxonomy like the CPV, the 3-digit level serves as the "basic level" of abstraction, meaning the most inclusive one at which categories could effectively mirror the structure of attributes perceived. Moving to a 2-digit level would be too abstract, losing the "attributes" necessary for waste mapping, while the 8-digit level provides no significant gain in attribute commonality for this specific research task. Similarly, this decision further ensured the dataset was "fit for use" by prioritizing representational consistency [39]. By standardizing heterogeneous entries into a 3-digit prefix, it moved beyond accuracy to prioritize interpretability and ease of understanding.

For the implementation of this standardization, the official EU CPV list was retrieved and cross-referenced with the dataset. This first allowed the addition of the associated English CPV code label names, complementing and validating the Italian text originally present; and second, it enabled the creation of hierarchy indicators specifying whether each entry was labelled as a division, group, class or category. In this manner, it was possible to identify the aggregation level of every record systematically, providing a structured basis for the subsequent reassignment steps.

Regarding entries carrying a 2-digit CPV code, a manual reassignment was carried out by consulting the descriptive information, related to its tender, attached to each record. These descriptions typically include the purpose of the purchase, the type of product involved, relevant technical characteristics and contextual details provided by the contracting authority. Based on this information, each entry was mapped to the most appropriate 3-digit CPV group.

The application of all these steps involved data handling that was performed through Python scripts executed in Jupyter Notebooks; these were used exclusively as an analytical tool by the author, hence not published as a separate output. This included the creation and removal of columns, the overwriting of fields, the cross-referencing within diverse datasets, the shortening of codes to the 3-digit level, among others. This approach made it possible to correct mistakes more rapidly, maintaining traceability.

4.3. Output: Harmonized Dataset and CPV-to-Waste Mapping

Following the reclassification steps described in the previous section, the procurement dataset became a structured resource suitable for input-output matching. As noted before, the final dataset after filters contains 19.457 records, corresponding to approximately 250 million euros in procurement expenditure distributed across the five years. Within these entries, the harmonization process produced 209 distinct CPV groups at the 3-digit level which the author named "Reassigned Groups", representing an aggregation layer that is both more internally consistent and analytically meaningful for waste mapping.

The cleaned dataset includes several columns that form the backbone of the analysis described in Chapter 5. The most important columns are:

- GP_GR = The standardized 3-digit CPV group code
- GP_GR_Desc = The English description of the CPV group, cross-referenced from the official EU list.
- Importo_lotto = Monetary value of the procurement entry
- Anno = Year of expenditure
- Denominazione_centro_costo = Cost centre, used to track departments under scope.

These fields jointly define the structure through which procurement flows can be linked to waste outputs.

From the full set of 209 CPV Reassigned Groups, only a subset was relevant for the four priority waste streams identified in Section 3.4. This subset was selected through the feasibility screening and Pareto logic described later in Chapter 5, which identifies which CPV groups plausibly generate each waste type. These groups and their mapped waste streams formed the input side of the matching workflow to be presented in Chapter 5.

5 Results III: Stream by Stream Procurement Analysis, Clustering and Proxy Estimation

This chapter presents the empirical results of mapping the cleaned procurement dataset comprising 19.457 records in 209 CPV Reassigned Groups against the four prioritized waste streams identified in Section 3.4. The analysis applies the screening and clustering workflow to each stream to identify relevant expenditure flows. The resulting data is organized into the cluster tables found in Sections 5.2 through 5.5, which contain the finalized data for the cluster tables introduced in Section 4.3. Every stream is analysed using consistent logic, though the execution includes documented adjustments for the specific material types being clustered.

5.1. General workflow and per-stream variations

The four streams analysed here followed the sequence in which the investigation unfolded, rather than according to the ranking produced by the prioritization matrix in Section 3.4. This reflects the sequence dictated by data availability and the analytical progression of the study.

Before entering the workflow, it is worth confirming explicitly that the four streams analysed here fall within the Operational Perimeter established in Chapter 2. Bulky Waste and Large WEEE both correspond to S3, the stream for long-life institutional purchases, and are fully within scope. Large WEEE was selected specifically through the prioritization matrix in Section 3.4, a choice that implicitly kept the analysis bounded to S3 since Small WEEE, which belongs to S2b and is excluded from the perimeter, ranked below the threshold. Hazardous Special Waste originates primarily from S2a consumables purchased directly by POLIMI, with selective S4 contributions where contractor involvement was evident, both of which fall within the defined scope. Paper Waste is the one nuanced case as the procurement side is anchored in S2a and therefore fully within the perimeter, but the waste measurement draws from AMSA data which, as documented in Section 3.2, unavoidably combines S2a and S2b flows since AMSA does not report POLIMI's paper separately from the surrounding buildings. Due to the nature of the study and the data provided, perfect adherence to the predefined analytical boundary was not always achievable. The Operational Perimeter was nonetheless maintained as the governing reference throughout, serving the same function it did in Chapter 2, which is to make the positioning of the study explicit and to ensure that any deviation is documented and reasoned rather than silent.

The transformation of procurement records into material proxies required a general eleven-step workflow, applied consistently across the four streams with documented adjustments where the material type required it. The process began with an operational definition for each stream in order to better understand what is considered within each waste stream, followed by a decision on whether to include service-coded entries based on their physical waste output. Third, a feasibility screen was applied to the 209 Reassigned Groups to establish a primary mapping with the waste type being assessed. As WEEE and HSW (Hazardous Special Waste) were linked to an initially large number of Reassigned Groups, the first screening allowed for the isolation of the specific groups that would move forward to the cleaning phase. Without this stage, the volume of data for WEEE and HSW would have remained unmanageable, whereas for Bulky and Municipal Paper, the smaller number of linked groups allowed for a more direct transition.

A fourth step provided an overlap cross-check for WEEE and HSW to confirm that the Reassigned Groups assigned to each stream were coherent, given that certain items can legitimately produce both electronic and hazardous waste. The fifth step defined the cleaning strategy based on the spending distribution of each stream. For Bulky Waste, the analysis targeted the single dominant group representing over 95% of the monetary value, while for WEEE, the three primary groups were selected for row-level cleaning. Conversely, for Municipal Paper and HSW, all rows within the identified group were cleaned to ensure accuracy despite the less predictable coding.

Sixth, selected records underwent row-level classification as “YES”, “NO” or “TO ANALYSE DEEPER”. Following this, entries labelled as “NO” or “TO ANALYSE DEEPER” were excluded from the material clusters, either because they were verified as unrelated to the waste stream or because they fell below the 15% monetary cutoff threshold. The remaining “YES” entries were then organized into material clusters derived from the records themselves, with Cluster 1 (IT & Computing) under the WEEE waste stream receiving specific subclustering. Ninth, a Pareto analysis identified the Class A clusters; and tenth, conversion ratios provided by the Waste Management and Procurement Departments were applied to selected clusters within

Class A to translate expenditure into estimated mass. Finally, results were compared with measured data as explained for each stream in the sections below.

The referenced figures from the waste side used for comparison also varied by stream, depending on the level of data granularity available. For Bulky Waste and Municipal Paper, the measured quantity reported in the Waste Typology for the year 2024 was used directly as the reference. For WEEE, data was only available at the CER code level for a subset of the full waste type, meaning the comparison was conducted against those specific codes rather than the total Large WEEE figure; similarly for Hazardous Special Waste, the reference aggregates two output groups within the whole waste type value reflected in the Typology summary table. The rationale for each choice is detailed in the corresponding stream section.

5.2. Bulky Waste

Under Italian law, waste from an institution like a university is classified as special waste as it originates from "service activities" [34]. This is why in the Waste Typology, this waste stream is under the Special macro group as it is managed through formal contracts (*appalti*) between the university and external service providers [40]. At POLIMI, bulky waste is legally identified by code CER 20 03 07, which includes furniture like chairs, tables, sofas, desks, wardrobes, large laboratory furniture, among others, that in practical terms are too large to fit into standard containers and therefore require dedicated collection [40]. Small objects that fit in regular bins and materials belonging to regulated streams such as WEEE, hazardous waste or other streams under special waste are excluded. Large metal wardrobes are excluded as they are sent to metal recycling. For the procurement-based analysis, CPV groups coded as services were excluded as their descriptions may refer to physical outputs but not in a sufficiently clear way to be reliably linked to bulky waste generation.

The mapping process identified two primary 3-digit CPV Reassigned Groups, which were "391 Furniture (*Mobili*)" and "392 Furnishing (*Arredamento*)". Group 391 accounted for approximately 92% of the total spend, making it the focus of deep cleaning. All rows within this Reassigned Group were reviewed at the row level and classified as BULKY, NOT BULKY or TO ANALYSE DEEPER. Rows in the latter two categories represented 13,6% of the monetary value across the three categories, which had a limited effect on the overall result. Consequently, only the confirmed "BULKY" rows were organized into eight functional material clusters listed below.

1) Office Seating: Consists of seating used in administrative and departmental offices. Chairs and stools are bulky because they are rigid, voluminous and cannot be placed in standard containers.

2) Office Tables and Desks: Refers to tables, desks and meeting workstations. Their dimensions, weight and composite materials require dismantling.

3) Storage Furniture: Includes cabinets, lockers, shelving and vitrines. These items are tall, heavy and often reinforced, making them difficult to compact.

4) Custom or Built-in Furniture: Refers to fixed or custom-made elements such as reception counters, wall systems and partitions, also requiring dismantling.

5) Laboratory Furniture and Technical Benches: Encompasses laboratory benches, fume hoods and technical tables. Their integrated systems and reinforced structures make them categorically bulky.

6) Classroom and Didactic Seating: Covers auditorium chairs, flip table systems and classroom benches. These items are rigid and often installed in rows, forming a separate bulky stream.

7) Common Area and Reception Furniture: Includes furniture used in lounges, break areas and reception zones. Sofas, waiting room seating and reception desks differ functionally from office or classroom items.

8) Mixed or Multi-Area Furniture Supply: Applies to mixed procurement lots that serve multiple environments and cannot be assigned to a single functional category.

Table 5.1 presents an ABC Pareto Analysis applied to these clusters, showing that Classroom and Didactic Seating accounted for approximately 41% of total bulky procurement spend.

Table 5.1: Bulky Pareto.

Clusters	Year					Total	Total %	% Accumulated	% Pareto Class
	2020	2021	2022	2023	2024				
6 - Classroom & Didactic Seating (Sedute didattiche / Arredi per aule)	139.601,73 €	138.840,80 €	156.685,28 €	138.880,00 €	3.484.708,00 €	4.058.715,81 €	41,13%	41,13%	
8 - Mixed / Multi-Area Furniture Supply (Forniture miste / multi-ambiente)	66.753,00 €	1.264.843,00 €	9.949,92 €	11.286,00 €	1.186,00 €	1.354.017,92 €	13,72%	54,85%	A
2 - Office Tables & Desks (Tavoli e scrivanie da ufficio)	339.106,95 €	524.460,85 €	244.073,50 €	118.739,42 €	29.624,05 €	1.256.004,77 €	12,73%	67,58%	
5 - Laboratory Furniture & Technical Benches (Arredi tecnici e da laboratorio)	93.989,19 €	113.879,81 €	210.106,36 €	313.407,51 €	244.949,80 €	976.332,67 €	9,89%	77,47%	
1 - Office Seating (Sedute da ufficio)	370.189,50 €	25.551,00 €	233.293,50 €	105.142,80 €		734.176,80 €	7,44%	84,91%	B
7 - Common Area & Reception Furniture (Arredi per aree comuni e reception)	237.649,30 €	151.730,11 €	83.494,50 €	70.900,00 €	74.842,80 €	618.616,71 €	6,27%	91,18%	
4 - Custom / Built-In Furniture (Arredi su misura / Arredi fissi)	35.918,00 €	347.276,00 €	12.747,50 €	56.208,50 €		452.150,00 €	4,58%	95,76%	C
3 - Storage Furniture (Arredi di stoccaggio / Armadi / Locker)	22.073,10 €	334.606,50 €	56.519,88 €	4.855,57 €		418.055,05 €	4,24%	100,00%	
Grand Total	1.305.280,77 €	2.901.188,07 €	1.006.870,44 €	819.419,80 €	3.835.310,65 €	9.868.069,73 €	100,00%		

Desks and tables were selected as the focal category for the input-output exercise as they represented one of the most consistent and analytically tractable furniture types. They appeared prominently in the procurement dataset, their material composition was relatively homogeneous, and their spending concentration placed them among the dominant Class A clusters identified through the Pareto analysis. From an operational perspective, they are also the furniture most frequently handled by the Waste Management Department, which is why jointly with the Procurement Department, both were able to agree on a shared conversion factor specifically for this category.

Thus, for the validation of the procurement-based proxy, the analysis compared the estimated annual mass entering the system with the measured waste leaving POLIMI as shown in Table 5.2.

The procurement dataset, once cleaned and restricted to the relevant clusters related to desks and tables, produced a yearly estimate of 160.430,64 kilograms. This value results from applying the agreed conversion factor of 10 €/kilogram to the five-year spending amount associated with desks and tables, which concentrates most of the monetary value within the bulky furniture category. To verify its robustness, the estimate was compared with an independent annual expenditure figure provided by the Procurement Department. When converted using the same factor, this value corresponded to 162.320 kilograms, closely matching the estimate derived from the cleaned procurement dataset.

On the waste side, the Waste Management Department provided two streams that were relevant for desks and tables. The Bulky Waste stream included intact items collected as whole units and amounted to 116.935 kilograms in 2024. The metal and wood stream contained dismantled furniture components, such as metal frames and wooden panels, and accounted for 47.000 kilograms in the same year. Since desks and tables may be discarded either whole or dismantled depending on how they were handled during removal, it seemed logical to consider both streams to approximate the total outflow of desks and tables. When combined, they amount to 163.935 kilograms, which is very close to the procurement-based estimate. Both sides' values are presented in Table 5.2.

Table 5.2: Bulky Results.

Component	Source	Value (kilograms/year)	Explanation
Procurement estimate	Cleaned procurement dataset	160.430,64	Conversion factor applied to five-year spending

Component	Source	Value (kilograms/year)	Explanation
Procurement validation	Procurement Department	162.320,00	Independent expenditure converted with same factor
Bulky Waste	Merged Waste Datasets	116.935,00	Intact desks and tables
Metal and Wood	Waste Management Department	47.000,00	Dismantled furniture components
Combined Waste	Bulky + metal and wood	163.935,00	Total outflow of desks and tables

5.3. Paper Waste

As explained before, POLIMI manages most of its waste as special waste, but paper follows a different route. It is officially defined as assimilated urban waste, referring to waste materials that are considered like domestic waste in both nature and quantity, but are formally managed by and entrusted to the municipal public collection service [40], [26]. Therefore, in practice the university adopts an operational definition that aligns with the characteristics of recyclable paper streams, referring to materials composed entirely of paper or cardboard, free from food residues, adhesives, plastic coatings, or chemical contamination such as office paper, A4 sheets, printer paper, notebooks, loose sheets, books, newspapers, among others. Items that do not meet these conditions are excluded, for example thermal paper, laminated items, plastic or PVC printed objects, banners, roll-ups, RFID cards.

Starting from this definition, the mapping process identified seven 3-digit CPV Reassigned Groups in the first screening, associated with the generation of paper waste. Among these, CPV "301 - Office machinery, equipment and supplies except computers, printers and furniture (*Macchine per ufficio, attrezzature e forniture, esclusi i computer, le stampanti e i mobili*)" displayed an atypically high expenditure because it contained both ICT equipment and paper reams, the latter being especially relevant. For this reason, all the rows belonging to the seven Reassigned Groups were "cleaned", hence classified as PAPER, NOT PAPER or TO ANALYSE DEEPER. Although service groups were not linked in the first CPV screening, they were included for this stream during the cleaning phase whenever descriptions clearly indicated paper-generating activities. This approach differs from the Bulky Waste stream where this link was not sufficiently evident. The last two categories were excluded. Rows classified as TO ANALYSE DEEPER represented less than 0,5% of the monetary value across the three categories, while NOT PAPER represented approximately 95%; but this was expected and simply reflected the mixed composition of CPV 301 where ICT equipment dominates expenditure. Only those labelled as PAPER met the operational definition and were grouped into the following twelve functional clusters:

1) A4/A3 Office Paper: Covers standard paper stocks used for printing, copying and writing, including plain sheets, coloured variants and basic office supplies made of paper.
2) Books & Monographs: Refers to bound printed works such as books, manuals, monographs and long-form publications.
3) Notebooks, Pads & Blocks: Groups writing notebooks, pads and block notes used for academic and administrative purposes.
4) Printed Envelopes: Contains envelopes with printed institutional or functional details.
5) Calendars & Agendas: Includes printed planning tools such as calendars, agendas and diaries.
6) Labels: Covers adhesive labels, printed stickers and identification tags used for filing or organization.
7) Printed Graphic Materials: Refers to communication prints such as posters, brochures, flyers and other graphic materials.
8) Specialty Paper: Includes non-standard paper types such as glossy, coated, textured or photographic paper used for specific printing needs.
9) Paper Forms / Sheets: Refers to structured documents such as pre-printed forms, administrative sheets and registration modules.
10) Cardboard Folders and Archival Boxes: Contains rigid paper-based storage support such as folders, document holders and archival boxes.
11) Newspapers: Refers to printed daily news publications and similar periodical news sheets.
12) Mixed Paper Stationery: Gathers assorted small paper items such as memo cards, sticky notes and other minor stationery not fitting other clusters.

Table 5.3 presents an ABC Pareto Analysis applied to these clusters, showing that the Books and Monographs cluster accounted for approximately 68% of total paper procurement spend.

Table 5.3: Paper Pareto.

Clusters	Year					Total	Total %	% Accumulated	Pareto Class
	2020	2021	2022	2023	2024				
2 - Books & Monographs (Libri e Monografie)	1.240.383,48 €	77.309,05 €	112.214,28 €	116.275,82 €	510.371,98 €	2.056.554,61 €	67,71%	67,71%	A
1 - A4/A3 Office Paper (Carta da ufficio A4/A3)	116.265,10 €	20.194,55 €	140.368,70 €	213.454,44 €	1.150,00 €	491.432,79 €	16,18%	83,90%	A
7 - Printed Graphic Materials (Materiale Grafico Stampato)	67.045,60 €	87.668,28 €	62.847,01 €	31.978,60 €	6.601,60 €	256.141,09 €	8,43%	92,33%	A
3 - Notebooks, Pads & Blocks (Quaderni, Blocchi e Taccuini)	668,00 €	8.670,28 €	38.398,70 €	27.287,50 €	15.468,62 €	90.493,10 €	2,98%	95,31%	B
12 - Mixed Paper Stationery (Cancelleria Mista Cartacea)	6.000,00 €			39.900,00 €		45.900,00 €	1,51%	96,82%	B
6 - Labels (Etichette)	21.650,00 €	5.170,00 €	175,00 €	3.450,00 €	820,00 €	31.265,00 €	1,03%	97,85%	B
10 - Cardboard Folders & Archival Boxes (Cartelline e Scatole d'Archivio)	7.275,00 €	2.615,90 €	3.170,51 €	5.926,00 €		18.987,41 €	0,63%	98,47%	C
4 - Printed Envelopes (Buste Stampate)		308,26 €	6.271,20 €	7.500,00 €	2.630,00 €	16.709,46 €	0,55%	99,02%	C
9 - Paper Forms / Sheets (Schede e Moduli Cartacei)	15.500,00 €					15.500,00 €	0,51%	99,53%	C
5 - Calendars & Agendas (Calendari e Agende)		90,01 €	1.911,15 €	3.130,00 €	2.440,00 €	7.571,16 €	0,25%	99,78%	C
8 - Specialty Paper (Carta Speciale)	4.992,00 €		954,00 €			5.946,00 €	0,20%	99,98%	C
11 - Newspapers (Quotidiani)	300,00 €			306,73 €		606,73 €	0,02%	100,00%	C
Total general	1.480.079,18 €	202.026,33 €	366.310,55 €	449.209,09 €	539.482,20 €	3.037.107,35 €	100,00%		

Books & Monographs and A4/A3 Office Paper clusters were selected as the reference categories for the input-output comparison, as they are the most homogeneous and quantitatively relevant components of Municipal Paper Waste. They also represent the paper types most frequently handled by the Waste Management Department, which allowed both departments to agree on specific conversion factors.

For office paper, the factor was derived from an average weight of 2,5 kilograms per ream and an average cost of 2,5 euros per ream, which corresponds to 1 euro per kilogram. For books, the agreed factor was 20 euros per kilogram.

Applying these factors to the cleaned procurement dataset produced a yearly estimate of 118.852,10 kilograms. This value combines 98.286,56 kilograms per year for A4/A3 Office Paper and 20.565,55 kilograms per year for Books and Monographs. These two categories also represented the dominant share of procurement spending within the Municipal Paper stream, as indicated by the Pareto analysis. Following the same approach used for Bulky Waste, the estimate was compared with an independent figure provided by the Procurement Department. When the spending amounts provided directly by the department were converted using the same factors, the resulting value amounted to 77.000 kilograms per year.

On the waste side, the Waste Management Department reported 121.462,67 kilograms of municipal paper collected in a year. This stream includes all recyclable paper discarded on campus, not only books and office paper but also mixed printed materials and administrative documents. Since the procurement estimate covers only the two focal clusters, it is reasonable that the waste figure is slightly higher. This proximity between the two values is shown in Table 5.4 below.

Table 5.4: Paper Results.

Component	Source	Value (kilograms/year)	Explanation
Procurement estimate	Cleaned procurement dataset	118.852,10	Office paper (1 €/kg); books (20 €/kg)
Procurement validation	Procurement Department	77.000,00	Centralised expenditure; same factors
Municipal paper waste	Waste Management Department	121.462,67	Total municipal paper collected on campus. Annual value from five-year data (2020-2024).

5.4. Waste Electrical and Electronic Equipment - WEEE

Similarly to Bulky Waste, Waste Electrical and Electronic Equipment (WEEE and *RAEE* in Italian) is treated as part of special waste and managed through formal contracts (*appalti*) with external service providers. At POLIMI, this refers to any equipment that relies on electrical currents or electromagnetic fields to function. It is treated as a regulated waste category that must be separated from ordinary municipal waste and managed through authorized collection systems [40]. In practice, it includes all devices, instruments and components used in offices, laboratories and teaching spaces that reach end-of-life and still qualify as electrical or electronic equipment under national legislation. When such items reach end-of-life, they are grouped and later assigned the appropriate EWC code (CER) before temporary storage and collection [41]. For the procurement-based analysis, the focus is restricted to the Large

WEEE stream, while Small WEEE and alkaline batteries are excluded as they follow different management channels. Since 2024, they are collected through a convention with the national coordination bodies for WEEE and batteries, the Comune di Milano and AMSA [42]. This initiative is managed by the *Area Infrastrutture e Servizi* and operates outside the *Appalto* system. Likewise, service-related rows were excluded in principle because, similarly to Bulky, they did not clearly reflect the creation of WEEE physical outputs.

During the initial mapping process, more than forty 3-digit CPV Reassigned Groups were identified as plausible generators of electronic waste. This number was significantly higher than for bulky or paper, reflecting the diversity of electronic equipment purchased by the university. Because these linked Reassigned Groups contained over 9.000 rows, a second screening was necessary to remove those that were unlikely to generate electronic waste, especially those with misleading names; despite filters, some service-related CPV Reassigned Group names remained. After this refinement, 36 CPV Reassigned Groups were retained for further analysis.

A first Pareto screening applied to these 36 groups identified three main monetary drivers: CPV 302 (Computer equipment and supplies), CPV 389 (Miscellaneous evaluation or testing instruments) and CPV 384 (Instruments for checking physical characteristics). Together, these three represented less than 5.000 rows, a more manageable subset for more detailed cleaning. Just as with paper, all rows within these three groups were reviewed and classified as WEEE, NOT WEEE or TO ANALYSE DEEPER by relying on the descriptive fields under "*oggetto*" columns that provided more detailed information for the classification. Of these three groups, the latter two represented together less than 7% of the monetary value across them; therefore, their exclusion was reasonable.

From the rows confirmed as WEEE, items were organized into the following nine functional clusters that reflect the main categories of electronic equipment purchased.

1) IT & Computing: Covers computing hardware such as laptops, desktops, workstations, tablets, iPads, and servers used for digital processing and institutional computing.
2) Lab Analysis and Spectroscopy: Refers to high-precision analytical instruments such as spectrometers, gas chromatographs, volatile organic compound analysers, dynamic mechanical analysers, haematology analysers, and plate readers.
3) Measurement and Sensors: Encompasses devices that measure physical quantities, including electromagnetic interference receivers, thermometric systems, laser scanners, accelerometers, and flow meters.

4) Additive Manufacturing and Tooling: Groups equipment for creating or shaping physical objects, including PolyJet and filament 3D printers, laser and blade plotters and cold spray systems.
5) Industrial and Specialized Lab: Covers large or heavy-duty laboratory infrastructure such as high-pressure reactors, microwave reactors, climatic chambers, sputtering chambers, and high-voltage fragmentation systems.
6) Medical and Biotech: Includes equipment for clinical or biological applications such as colonoscopes, cell sorters, incubators and syringe pumps.
7) Audiovisual and Digital Signage: Refers to systems for communication and display, including LED walls, professional audio systems, video conferencing kits from Poly or Logitech, digital boards, and auditorium upgrades.
8) Lab Consumables and Small Tools: Covers small laboratory tools and consumables such as pipettes, heating plates, pH meters, specialized glassware, and manual hand tools.
9) Electronic Components and Boards: Includes electronic elements for prototyping, such as microcontrollers like STM32 or Arduino, printed circuit boards, software-defined radio boards, individual sensor chips and wiring kits.

Table 5.5 presents an ABC Pareto Analysis applied to these clusters, showing that the IT & Computing cluster accounted for approximately 28% of total large WEEE procurement spend.

Table 5.5: WEEE Pareto.

Clusters	Year					Total	Total %	% Accumulated	% Pareto Class
	2020	2021	2022	2023	2024				
1 - IT and Computing (IT e Informatica)	1.924.553,64 €	3.825.984,55 €	1.497.301,96 €	2.071.051,59 €	1.159.704,81 €	10.478.596,55 €	26,74%	26,74%	
5 - Industrial & Specialized Lab (Laboratorio Industriale e Specializzato)	394.835,89 €	136.099,47 €	940.113,36 €	5.747.553,32 €	1.222.086,67 €	8.440.688,71 €	21,54%	48,27%	A
2 - Lab Analysis & Spectroscopy (Analisi di Laboratorio e Spettroscopia)	629.313,89 €	920.514,57 €	1.635.334,18 €	2.004.863,91 €	560.068,50 €	5.750.095,05 €	14,67%	62,95%	
3 - Measurement & Sensors (Misurazione e Sensori)	747.040,22 €	437.669,02 €	845.492,30 €	1.922.520,95 €	1.071.360,85 €	5.024.083,34 €	12,82%	75,76%	
4 - Additive Mfg & Tooling (Manifattura Additiva e Attrezzature)	825.388,97 €	730.281,17 €	268.105,78 €	2.932.282,68 €	126.547,07 €	4.882.605,67 €	12,46%	88,22%	B
7 - Audiovisual & Digital Signage (Audiovisivo e Segnaletica Digitale)	2.353.452,23 €	174.624,04 €	49.481,25 €	140.357,60 €	128.753,74 €	2.846.668,86 €	7,26%	95,49%	
6 - Medical & Biotech (Medicale e Biotecnologie)	24.019,30 €	16.373,90 €	1.870,00 €	476.806,00 €	751.193,38 €	1.270.262,58 €	3,24%	98,73%	
9 - Electronic Components & Boards (Componenti e Schede Elettroniche)	43.732,36 €	62.499,12 €	34.689,04 €	156.985,55 €	2.950,80 €	300.856,87 €	0,77%	99,50%	C
8 - Lab Consumables & Small Tools (Consumabili da Laboratorio e Piccoli Strumenti)	41.303,09 €	16.528,68 €	109.524,79 €	20.340,37 €	10.056,40 €	197.753,33 €	0,50%	100,00%	
Total general	6.983.639,59 €	6.320.574,52 €	5.381.912,66 €	15.472.761,97 €	5.032.722,22 €	39.191.610,96 €	100,00%		

Although IT & Computing was only moderately ahead of the next cluster in monetary terms, it remained the largest and most diverse set of items procured by the university. In general terms, it encompasses digital equipment, yet within it there were substantial differences in price, weight and material composition. For this reason, the cluster was examined in greater detail and subdivided into the ten functional subclusters shown below. Applying a single conversion factor across the entire cluster would have produced an unrealistic mass estimate. This requirement for granularity was reinforced during the last meeting with the Waste Management and Procurement Departments, in which the representative of the Waste Management Department noted that the heterogeneity of products within the relevant CER code is itself a structural feature of how WEEE data is recorded on the output side. Accordingly, the subcluster boundaries were drawn not only from the internal logic of procurement records but also from the CER classification structure provided by the Waste Management Department, so that each could be mapped as cleanly as possible to one of the three relevant codes.

Thus, subclustering shown in Table 5.6 on the procurement side was a necessary and deliberately output-aligned step to make the subsequent comparison methodologically defensible. In contrast, the second dominant cluster, Industrial and Specialized Lab, was not further subdivided despite its high monetary value, as its size was driven by three exceptional capital investments in 2023 that behaved more like long-life infrastructure than recurring WEEE flows. Moreover, it is inherently less actionable from a circular economy perspective as it offers fewer practical levers for recurring recovery or redesign interventions.

1.1) Standard Laptops: Covers portable computers for everyday institutional use, including general-purpose laptops, notebooks used for teaching, administration and standard digital tasks.

1.2) High-End Laptops / Mobile Workstations: Refer to high-performance portable computers designed for demanding applications such as CAD, simulation, rendering and advanced data processing.

1.3) Standard Desktops & Micro PCs: Encompasses fixed computing units for office or light laboratory use, including desktop PCs, compact micro-PCs in small forms.

1.4) Fixed Workstations: Groups high-performance tower computers equipped with professional GPUs, used for simulation, rendering, modelling and other computation-intensive workloads.

1.5) Servers, Storage & HPC Infrastructure: Covers centralized computing hardware such as rack servers, compute nodes, storage systems, NAS units and other components supporting institutional IT infrastructure.

1.6) Tablets & Mobile Interfaces: Includes handheld touchscreen devices such as tablets, iPads, hybrid tablets and smartphones used for mobile access, teaching support and lightweight digital tasks.

1.7) Monitors, Displays & TVs: Refers to standalone visual output devices including computer monitors, professional displays and televisions used for workstations, teaching spaces and signage.

1.8) External Peripherals & Networking Accessories: Covers standalone external devices that support computing activities, including input peripherals, webcams, docking stations, networking accessories and barcode readers.

1.9) Internal Components & Upgrades: Includes internal electronic components purchased to upgrade or repair existing devices, such as RAM modules, processors, motherboards, internal SSDs and expansion cards.

1.10) Printing, Imaging & Office Communication Equipment: Refers to standalone office machines for printing, copying, scanning and fixed-line communication, including printers, multifunction devices, scanners and desk phones.

Table 5.6: Subclusters from Cluster 01.

Clusters	Year					Total	Total %	% Accumulated
	2020	2021	2022	2023	2024			
1.1 - Standard Laptops (Laptop Standard)	767.936,13 €	1.019.873,05 €	502.775,16 €	441.873,63 €	277.952,68 €	3.010.410,65 €	28,73%	28,73%
1.5 - Servers, Storage & HPC Infrastructure (Server, Archiviazione e Infrastruttura HPC)	322.890,98 €	735.577,97 €	475.099,00 €	331.559,77 €	268.231,06 €	2.133.358,78 €	20,36%	49,09%
1.3 - Standard Desktops & Micro PCs (Desktop Standard e Micro PC)	273.387,36 €	620.519,90 €	126.327,86 €	588.797,23 €	150.707,65 €	1.759.740,00 €	16,79%	65,88%
1.4 - Fixed Workstations (Tower/GPU) (Workstation Fisse (Tower/GPU))	169.590,33 €	912.498,69 €	95.625,59 €	150.435,00 €	192.466,43 €	1.520.616,04 €	14,51%	80,39%
1.2 - High-End Laptops / Mobile Workstations (Laptop di Fascia Alta / Workstation Mobili)	174.113,66 €	289.651,70 €	208.951,09 €	286.507,84 €	139.462,12 €	1.098.686,41 €	10,49%	90,88%
1.8 - External Peripherals & Networking Accessories (Periferiche Esterne e Accessori di Rete)	92.022,42 €	161.397,68 €	23.312,02 €	35.501,73 €	54.590,76 €	366.824,61 €	3,50%	94,38%
1.6 - Tablets & Mobile Interfaces (Tablet e Interfacce Mobili)	52.623,65 €	36.028,29 €	10.534,75 €	210.426,11 €	53.531,49 €	363.144,29 €	3,47%	97,84%
1.9 - Internal Components & Upgrades (Componenti Interni e Aggiornamenti)	66.956,64 €	41.756,49 €	34.054,80 €	16.859,12 €	17.815,47 €	177.442,52 €	1,69%	99,54%
1.7 - Monitors, Displays & TVs (Monitor, Display e TV)	2.176,47 €	6.601,78 €	20.621,69 €	9.091,16 €	4.947,15 €	43.438,25 €	0,41%	99,95%
1.10 - Printing, Imaging & Office Communication Equipment (Apparecchiature di Stampa, Imaging e Comunicazione da Ufficio)	2.856,00 €	2.079,00 €				4.935,00 €	0,05%	100,00%
Total general	1.924.553,64 €	3.825.984,55 €	1.497.301,96 €	2.071.051,59 €	1.159.704,81 €	10.478.596,55 €	100,00%	

As explained before and confirmed during the meetings with the involved departments, WEEE's quantities are tracked by CER codes rather than by product category. Along these lines, three codes were identified as relevant for the equipment types covered in this analysis. CER 16 02 13* covers end-of-life items such as monitors, televisions and UPS units [26], which are categorized as hazardous due to the presence of toxic display components or lead-acid batteries (unlike lithium batteries). CER 16 02 16 covers components removed from end-of-life equipment, such as circuit boards, cables, RAM sticks, processors and motherboards [25]. And CER 16 02 14 encompasses most of the remaining items, such as laptops, desktops, servers, peripherals [25]. Other CER codes that technically also relate to electrical and electronic equipment were excluded from this analysis in principle due to the separation of Small WEEE and alkaline batteries already above. Additionally, as explained by the Waste Management Department representative, codes outside the 16 02 family, such as 20 01 21 covering neon lamps and fluorescent tubes, represent waste that is generated during maintenance activities and under Italian law the maintenance contractor is legally responsible for its collection and disposal. As a result, quantities recorded by POLIMI under such codes tend to capture only exceptions and non-standard situations, making them structurally unreliable as a comparison reference.

Although three CER codes were identified as relevant to the equipment types covered in this analysis, the input-output exercise was performed exclusively against CER 16 02 14. This code aggregates the largest number of subclusters (1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8 and 1.10), representing the dominant share of both procurement expenditure and measured waste quantities, and is the only code for which the procurement-to-waste mapping was methodologically coherent. On the other hand, CER 16 02 13 covers only subcluster 1.7, which represents a comparatively small share of the total cluster under scope; and CER 16 02 16 presents a more fundamental mapping issue represented by the fact that its items include components stripped from full devices at the moment of disposal, meaning it is a downstream byproduct of device procurement rather than a direct counterpart to subcluster 1.9 purchases, which represent standalone components bought for repair or upgrade purposes. Just for reference, CER 16 02 13 recorded 2.470, 4.110 and 3.199 kilograms in 2023, 2024 and 2025 respectively; and CER 16 02 16 recorded 380,00, 0,00 and 1.050,00 kilograms in the same years.

For the conversion of monetary value to mass of subclusters under Cluster 1 (IT & Computing) associated with CER 16 02 14, the Procurement Department provided conversion rates for subclusters 1.1, 1.5, 1.3, 1.4 and 1.2. These values, set at 350, 200, 100, 200 and 500 €/kilogram, reflected a value-density coefficient logic, meaning they represented the ratio between negotiated institutional purchase price and net hardware weight. The pattern clearly showed that the university paid higher amounts for lighter and more technologically advanced components. To remain consistent with this reasoning, the remaining subclusters not addressed by the Procurement Department were independently estimated by the author following the same value-density logic. Subcluster 1.6 received the highest rate at 850 €/kilogram as it includes extremely light and expensive items, while 1.8 and 1.10 were assigned much lower values, 45 and 30 €/kilogram, respectively. Subcluster 1.10 contains heavier items like printers that are also more expensive per unit, while subcluster 1.8 groups lighter and cheaper items like mice, which explains their proximity. These final rates were obtained by averaging prices and weights of the most representative items inside each subcluster.

The application of these conversion rates to the cleaned procurement dataset produced a yearly estimate of 11.081,84 kilograms as shown in Table 5.7. This value results from averaging the total five-year procurement-based mass of 55.409,21 kilograms across all eight subclusters mapped to CER 16 02 14. On the waste side, the Waste Management Department provided annual quantities recorded under this code of 12.810,00 kilograms in 2023; 20.510,00 kilograms in 2024; and 20.694,00 kilograms in 2025, yielding a yearly average of 18.004,67 kilograms.

The factors behind the higher resulting gap in comparison with the other streams from the alignment check between the two sides are further discussed in Chapter 6.

Table 5.7: WEEE Results.

Component	Source	Value (kilograms/year)	Explanation
Procurement estimate	Cleaned procurement dataset	11.081,84	Averaged annual value from years 2020 to 2024
Large WEEE Waste	Waste Management Department - CER 16 02 14	18.004,67	Averaged annual value from years 2023 to 2025

Beyond the WEEE comparison, the mass estimates established for Cluster 1 also allowed for a secondary derived computation. During discussions with the Procurement Department representative, it was noted that IT hardware deliveries at POLIMI arrive packaged with cardboard boxes and polystyrene foam inserts, both of which become waste at the point of unboxing and are not formally tracked through the WEEE channel. The Procurement Department set the packaging estimate at 250 grams of cardboard and 50 grams of foam per kilogram of IT hardware, applying this to all eight subclusters linked to CER 16 02 14. On a yearly basis, this corresponds to about 2.770 kilograms of cardboard and 554 kilograms of polystyrene foam generated by IT purchases. These figures cannot be validated against measured waste data because the central compactor aggregates packaging from all sources, but they still provide a first indicative estimate of the packaging waste linked to IT procurement and show how one cluster can generate waste streams handled through different management channels.

5.5. Hazardous Special Waste

As with WEEE and Bulky Waste, this waste stream is treated as part of special waste and managed through formal contracts (*appalti*) with external service providers, but with a stricter regulatory workflow given its hazardous nature. According to Italian law, these wastes are identified with an asterisk (*) in the European Waste List (CER) that signals the possession of one or more hazardous characteristics as defined by national environmental law that also states that this waste stream is produced primarily through the university's research, teaching and administrative "service activities" [34]. In practice, this includes chemical waste, contaminated packaging, absorbents and Personal Protective Equipment, fluorescent tubes, mercury lighting, batteries removed from devices, lithium and nickel-cadmium batteries, lead-acid batteries, biomedical waste from research and WEEE. Nonetheless, in this thesis, all WEEE was excluded from the hazardous special waste stream to avoid overlapping with its dedicated analysis.

The first analytical step of the initial mapping process yielded 38 3-digit CPV Reassigned Groups linked to the generation of Hazardous Special Waste. Two groups, 331-Medical Equipment and 423-Industrial or Laboratory Furnaces and Incinerators, overlapped with WEEE streams; after closer inspection, only group 331 was retained as it contained items that could legitimately generate both hazardous waste and WEEE. This refinement led to 37 groups. Following the approach for paper waste, service-related CPV 3-digit codes were not excluded a priori, since hazardous waste can arise from laboratory work, chemical handling, maintenance, medical services or other services.

The dataset was further filtered by cost centre, retaining only departments known to operate laboratories that generate hazardous waste tracked in POLIMI's CER records through the *Appalto* channel, including Chemistry, Aerospace Sciences, Mechanics, Physics, Electronics and Bioengineering, Energy, and Civil and Environmental Engineering. Administrative departments and those without active experimental lab operations were excluded, as their procurement records do not produce documented hazardous outputs within this management channel.

Analogously to the WEEE workflow, all rows belonging to these groups were then cleaned and classified as HSW, NOT HSW or TO ANALYSE DEEPER. Although for this case HSW represented only 11,64% of the monetary value across these three labels, a more detailed inspection showed that these were records that truly and more clearly generated hazardous outputs.

As with WEEE, the CER code structure from the output side informed the clustering architecture on the procurement side for Hazardous Special Waste, as the Waste Management Department only provided weight measurements aggregated in two groups for the comparison exercise: one grouping Oil & Emulsions, and the other encompassing all remaining hazardous fractions. An initial clustering of HSW had been developed prior to institutional engagement; however, following discussions with the involved departments made it clear that several of the originally defined clusters did not correspond to waste fractions that the university actually records under HSW, therefore the clusters were realigned so each would map unambiguously to one of these two output groups, making the subsequent matching exercise methodologically coherent. Below are the final four defined clusters where Cluster 1 maps to the Oil & Emulsions group, while Clusters 2, 3, and 4 all map to the "Others".

1) Technical Oils and Industrial Fluids: Maintenance fluids such as lubricating and hydraulic oils and cooling liquids, acquired in litres or gallons.
2) Bulk and Basic Lab Chemicals: Pure chemicals and solvent mixtures in liquid or solid form, including commodity solvents, inorganic acids, and mid-range analytical reagents.
3) High-Value Biological & Specialized Kits: Pre-packaged analytical kits, biological cultures, cell preparations and specialized dyes typically supplied in small-volume vials or multipacks.
4) Contaminated Solid Consumables: Physical solid items such as gloves, syringes, pipettes, laboratory glassware and cleanroom garments that become hazardous through contamination during use.

Table 5.8 presents an ABC Pareto Analysis applied to these clusters, showing that the Bulk & Basic Lab Chemicals cluster accounted for approximately 77% of total HSW procurement spend.

Table 5.8: Hazardous Special Pareto.

Clusters	Year					Total	Total %	% Accumulated	% Pareto Class
	2020	2021	2022	2023	2024				
2 - Bulk & Basic Lab Chemicals (Prodotti Chimici Sfusi e di Base per Laboratorio)	539.237,72 €	528.014,33 €	466.572,64 €	471.445,12 €	220.020,93 €	2.225.290,74 €	77,00%	77,00%	A
4 - Contaminated Solid Consumables (Consumabili Solidi Contaminati)	84.884,37 €	93.127,92 €	55.277,62 €	69.432,35 €	26.322,24 €	329.044,50 €	11,39%	88,38%	B
3 - High-Value Biologicals & Specialized Kits (Materiali Biologici ad Alto Valore e Kit Specializzati)	32.899,13 €	41.705,70 €	61.214,17 €	83.090,37 €	62.379,00 €	281.288,37 €	9,73%	98,11%	C
1 - Technical Oils & Industrial Fluids (Oli Tecnici e Fluidi Industriali)	39.769,10 €	1.355,48 €	1.828,83 €	8.211,33 €	3.356,54 €	54.521,28 €	1,89%	100,00%	C
Total general	696.790,32 €	664.203,43 €	584.893,26 €	632.179,17 €	312.078,71 €	2.890.144,89 €	100,00%		

At the time of data collection, the Procurement Department’s cooperation was focused on the other three waste streams, where institutional pricing benchmarks were also clearer and more readily available to the Department’s representative. However, the extension of the same exercise to hazardous materials was not pursued similarly, as it would have required a separate dedicated effort outside the scope of what could be requested in the available timeframe. Therefore, conversion rates were independently estimated through a benchmarking exercise grounded in market pricing and product catalogues for the most representative items within each cluster. Rather than assigning single fixed values, each factor was derived as the midpoint of a bounded price range, so that applying the lower and upper bounds instead of the midpoint allows the derivation of a corresponding mass range for each one, providing a direct indication of the estimation uncertainty associated with each conversion factor.

The resulting point estimates, set at 2,25 €/kilogram for Cluster 1, 24,4 €/kilogram for Cluster 2 and 10,9 €/kilogram for Cluster 4, reflect material density and value logic where cheaper and heavier materials such as bulk oil receive lower rates, while lighter and more specialized items such as laboratory chemicals and protective garments receive progressively higher ones. Cluster 1 received the lowest rate, derived as the midpoint of the range 1,5-3 €/kilogram for bulk mineral and lubricant oils, consistent with bulk mineral oil pricing for hydraulic and lubricant grades in the Italian and European industrial market, estimated from a general review of major supplier catalogues including ENI and Castrol. Cluster 2 was assigned a rate derived from a three-tier spend-weighted formula present within the cluster, where each tier was constructed as the midpoint of a bounded interval. At the lower end were commodity solvents such as ethanol, within a range of 1-3 €/kilogram; in the middle, mid-range inorganic chemicals and acids, within a range of 10-20 €/kilogram; and at the upper end, high-value analytical reagents, within a range of 30-80 €/kilogram; all consistent with institutional pricing documented in academic procurement catalogues from major European laboratory suppliers (including Merck, VWR, and Fisher Scientific for Italian academic buyers), which were consulted for benchmarking purposes.

Cluster 4’s rate was similarly calculated by weighting two categories within the cluster: light consumables such as gloves, bulk autoclave waste bags, absorbent bench paper and basic polyethylene disposables, assigned a price range of 3-5 €/kilogram reflecting bulk institutional procurement pricing for lab plasticware and standard nitrile disposables per Fisher Scientific and VWR Italy catalogues; and heavier specialized garments such as cleanroom suits and Tyvek-type coveralls, assigned a range of 20-34 €/kilogram grounded in European PPE supplier pricing for disposable lab garments in institutional volume orders, estimated from a general review of supplier pricing including Heller-Medizintechnik and comparable distributors.

No conversion factor was assigned to Cluster 3 for the following reason. Cluster 3, referred to as High-Value Biological & Specialized Kits, was excluded from the input-output matching, as the implied €/kilogram ratio for biological materials such as PCR kits, cell cultures and fluorescent dyes operates in ranges exceeding 5.000 €/kilogram, which reflects that even a small uncertainty in the assumed rate would produce mass estimates whose variance far exceeds their informational value. Precise waste quantities cannot be estimated from procurement data and must be obtained directly from the Waste Management Department as part of the follow-up work for this study.

The application of these conversion rates to the filtered and cleaned procurement dataset produced a total procurement-based mass of 145.619,71 kilograms across the three clusters included in the exercise. Averaging this figure across the five-year period gives 4.846,34 kilograms per year attributable to Cluster 1, aligned with the Oil & Emulsions output category, and 24.277,60 kilograms per year from Clusters 2 and 4 combined, aligned with the "Others" category. On the waste side, the Waste Management Department provided annual quantities for both groups: Oil & Emulsions recorded 3.622,00 kilograms in 2023; 1.067,00 kilograms in 2024; and 6.006,00 kilograms in 2025, yielding a yearly average of 3.565,00 kilograms; while "Others" recorded 28.961,00 kilograms in 2023; 27.338,00 kilograms in 2024; and 23.374,50 kilograms in 2025, yielding a yearly average of 26.557,83 kilograms. Table 5.9 shows the aggregated values for reference.

Table 5.9: Hazardous Special Results.

Component	Source	Value (kilograms/year)	Explanation
Procurement estimate	Cleaned procurement dataset	29.123,94	Average annual value from years 2020 to 2024
Hazardous Special Waste	Waste Management Department data - Oil & Emulsions + Others	30.122,83	Average annual value from years 2023 to 2025

5.6. Proxy Assessment

Sections 5.2 through 5.5 applied the procurement screening and clustering workflow independently for each of the four prioritized waste streams. The results of these sections are consolidated below into a summary view displayed in Table 5.10, placing the estimates from the procurement-based mass analysis alongside the available waste reference figures. The evaluation of the difference is further explored in Chapter 6, along with the interpretation and discussion of the results.

Table 5.10: Summary Table.

Stream	Procurement Estimate from Dataset (€→kilograms)	Measured Waste Reference (kilograms)
Bulky	160.430,64	163.935,00 [1]
Paper	118.852,10	121.462,67 [2]
WEEE	11.081,84	18.004,67 [3]
Hazardous Special	29.123,94	30.122,83 [4]

Table notes

1. This is the combined sum of two distinct physical streams reported by the Waste Management Department, which are intact Bulky Waste (116.935 kilograms) and dismantled metal or wood components (47.000 kilograms) as detailed in Section 5.2.
2. This value represents all municipal paper collected across the campus, while the procurement estimate is focused specifically on the two primary clusters (Office Paper & Books). This difference in scope is methodologically coherent as the procurement-based estimate is expected to be lower than the total campus-wide output.
3. This number represents the average annual value derived from three consecutive years' figures (2023-2025) and only for CER 16 02 14.
4. This value aggregates the two output groups within HSW (Oil & Emulsions & Others).

6 Discussion

6.1. Discussion of Results

The primary research question of this study asked whether procurement spending data, once cleaned and reclassified, could serve as a meaningful proxy for estimating material waste generation at POLIMI. Based on empirical evidence collected across the four prioritized waste streams, the answer is yes, provided that the proxy is applied under specific conditions. The study demonstrated that financial data, despite its original administrative purpose, contains the necessary information to reconstruct material flows at an institutional level. These findings align with the methodological principle that a correct evaluation of environmental performance depends on the choice of adequate raw data and the relational structure built between those data points [12], and support the use of administrative records as a legitimate input to institutional waste accounting when direct measurement is unavailable.

The degree of alignment between the procurement estimates and the measured waste reference was evaluated by directly comparing the two figures for each stream. Given the screening-level purpose of the assessment and the institutional consensus-based nature of the conversion factors, the goal was not to achieve perfect numerical correspondence but rather to identify the structural conditions under which the proxy performs reliably and where it requires methodological correction.

The summary Table 5.10 in Section 5.6 consolidates the results addressed in this section. Three out of four streams showed close alignment with measured waste data, providing concrete empirical evidence of the proxy's validity across compositionally diverse waste categories. Bulky Waste, Municipal Paper and Hazardous Special Waste each produced estimates that demonstrated strong consistency with their respective reference values. WEEE, however, showed a larger divergence, for reasons that are themselves analytically informative and discussed later.

Before interpreting each stream individually, a pattern worth noting ran across all four results: the procurement estimate was consistently lower than the measured waste reference, producing a systematically negative gap. This is not a calibration error but a structural feature of the method. The waste side captured everything that physically left the campus regardless of origin, including flows from students and campus users (S2b) and from contracted service providers (S4), neither of which pass through

POLIMI's procurement system. The procurement estimate covered only what the institution directly purchased under S2a and S3. The degree of underestimation is therefore itself informative about how much of each stream originates outside institutional purchasing.

For Bulky Waste, the close alignment was notable given that furniture is a long-life asset. Desks and tables purchased today may not appear in waste records for a decade or more. The result supported the idea that in a large institution like POLIMI, furniture procurement is sufficiently stable. Within a five-year window, this stability allows annual disposal to reflect annual procurement when viewed across the whole system. This assumption holds if purchasing patterns have remained relatively stable across the preceding decade. The close match between the independent procurement validation figure (162.320 kilograms) and the cleaned dataset estimate (160.430 kilograms) supports this. The 1,2% difference showed that the manual cleaning process produced a reliable enough input rather than a distortion of the data. The category is also physically homogeneous, with the spending concentrated in the analysed cluster for the matching exercise, further reducing the conversion factor uncertainty. Together, these explain the consistent directional alignment between the two sides for this waste fraction.

For Municipal Paper, interpreting the high correspondence match requires distinguishing between the two clusters that form the procurement estimate. By mass, A4/A3 Office Paper accounted for 82,7% of the estimated total, while Books and Monographs accounted for 17,3%. This distribution, which reflects the high euro per kilogram conversion rate of books (20 €/kilogram) relative to office paper (1 €/kilogram), means the aggregate is governed by a short-life flow. Office paper does not circulate internally, get repaired or redistributed before disposal: the link between procurement and waste generation is structurally tight and temporally close, producing no meaningful stock effect. For books, the situation differs as they are long-life items where the temporal coupling assumption is less straightforward. However, for a large institution with continuous and diversified acquisitions across departments and library holdings, aggregate annual disposal can be expected to approximate aggregate annual procurement under steady-state conditions, provided that purchasing patterns have remained relatively stable over time. This is an assumption rather than a confirmed finding and is acknowledged as such. Additionally, the procurement estimate covered only the two primary clusters, while the waste reference of 121.462,67 kilograms included all recyclable paper collected on campus, such as mixed printed materials, administrative documents and packaging. The fact that the gap for this waste type is small suggests that the paper fractions not included in the model either contribute very little to overall mass or are too small to meaningfully affect the overall result. As for the Procurement Department's validation figure of 77.000 kilograms, its distance from the dataset estimate is likely due to a difference in scope. The department figure probably reflects only centralized institutional purchases, while the cleaned dataset also captures decentralized orders and paper items embedded in mixed procurement entries. This explanation fits the structure of the dataset, although it was not explicitly confirmed during data collection meetings and is therefore presented as a reasoned hypothesis rather than a verified conclusion.

For WEEE, the procurement-based estimate produced 11.081,84 kilograms per year against a measured output of 18.004,67 kilograms per year for CER 16 02 14, a significantly more pronounced difference than observed in the other three streams. Three structural factors could explain this result, none of which could be considered methodological flaws.

The first and most significant is the stock effect inherent to long-life S3 flows. IT equipment purchased at POLIMI typically remains in use for five to eight years before disposal [24]. The procurement data window covers 2020 to 2024, but the waste measured by the department in 2023 and 2024 includes devices purchased well before that window, in years that fall outside the procurement estimate timeframe considered in the study. This temporal mismatch is a known limitation of single-window procurement datasets when applied to long-life equipment, directly addressed in the literature by the Swiss UAS study cited in Chapter 2, which proposed annualizing IT procurement as a fraction of a multi-year bulk to compensate for this lag.

The second factor concerns the scope of CER 16 02 14 relative to the procurement subclusters. As confirmed by the Waste Management Department during some meetings, the heterogeneity of products within this code means that the waste-side quantity aggregates equipment types beyond what the procurement subclusters fully capture. Scientific instruments, specialized lab devices and contractor-managed replacements may all exit the campus under CER 16 02 14 without a corresponding entry in the procurement dataset.

The third factor is the structural incompleteness of CPV records below the mandatory coding threshold. During the meetings with the departments, it was explained that purchases below approximately 40.000 euros were historically coded through an AI-predicted system that could indeed present some errors when assigning a CPV code to the entries or simply not assigning a valid code at all. This is not an isolated data quality problem but a known structural challenge of the procurement environment: the difficulty of collecting data that is not legally required but relevant for environmental performance evaluation is a recognized institutional constraint and it affects the input side of any procurement-based proxy applied to categories dominated by small-value purchases. A substantial share of IT purchasing at POLIMI, including individual peripherals, departmental accessories and smaller software-bundled hardware, falls below this threshold and is therefore underrepresented on the input side.

Taken together, these three factors produce a procurement estimate that is systematically lower than the measured output, not because the proxy logic is wrong, but because it operates on an incomplete and temporally lagged input. This finding is methodologically relevant: for short-life flows such as paper, procurement-based proxies perform well because purchase and disposal are temporally aligned, while for long-life S3 flows like IT equipment, the proxy captures future waste potential rather than current disposal patterns. The structural constraints underlying this result are addressed as part of the study limitations in Section 6.7.

For Hazardous Special Waste, the procurement estimate of 29.123,94 kilograms per year aligned closely with the measured reference of 30.122,83 kilograms per year, confirming the directional pattern of close alignment observed for Bulky and Paper. This result is particularly notable because the conversion factors for this stream were not provided directly by the departments but were independently estimated through a benchmarking exercise based on market pricing from institutional catalogues, as explained in Chapter 5. The fact that the aggregated comparison showed close alignment despite this methodological difference suggests that the cluster structure captured the dominant hazardous flows with sufficient accuracy. At the sub-category level, the Oil & Emulsions group showed a slight overestimate, which may reflect a purchasing-to-consumption lag for bulk fluids stored before use, while the Others category showed a slight underestimate consistent with the structural pattern observed across all streams and attributable to S2b and S4 flows not captured on the input side. It is also relevant to mention that chemical waste quantities can be influenced by laboratory practices, such as the disposal of partially used reagents, and by the inclusion of container weight in the recorded quantities, both of which introduce small systematic biases on the waste side that cannot be isolated with the available data.

Across all four streams, the results confirm that the effectiveness of the procurement-to-waste proxy depends on three conditions operating simultaneously. First, the waste category must be physically discrete, meaning the relationship between what is purchased and what is eventually discarded must be sufficiently traceable. Second, the CPV mapping must be auditable, meaning that the link between each procurement record and its associated waste type must be documentable and feasible, and the precision and quality of the mapping must function as an explicit, measurable attribute of the method rather than an implicit assumption, consistent with the metrological principle that data quality characterization is a prerequisite for reliable environmental performance measurement [12]. And third, the conversion factors must be logical and preferably grounded in institutional consensus or validated market benchmarks. Making these analytical boundaries explicit is not only a methodological requirement but a condition for institutional trust [6]. Where a conversion factor involves professional judgment, transparency about how and by whom those values were established is what allows managers and sustainability officers to rely on the results for decision-making.

Where all three conditions held, the proxy produced estimates in close alignment with measured data. Where they did not fully hold, as with WEEE, the divergence was predictable and interpretable rather than unexplained noise.

6.2. Methodological Coherence of the Empirical Approach

From the outside, the different structures presented throughout this thesis might initially appear fragmented; however, they follow a chain of analytical dependencies where each step connects to the next. The five Concepts established the environmental domains, while the Streams identified the specific flows within those domains. The Stream classification provided the necessary rules for attribution that the Concepts alone could not offer. Its logic directly informed the Operational Perimeter, providing a clear rationale for the inclusion of specific flows. Without the Streams, the Operational Perimeter would lack a coherent justification for its boundaries.

Once defined, the Operational Perimeter served as a functional filter required to move the research from theory into empirical practice. It allowed for the systematic application of filters to the procurement data, providing the narrowed context needed to start the actual analysis. Without these filters, the material study would have been distorted by irrelevant data.

The original plan was to use procurement records as a direct mass estimate for the Material Concept, but the inherent characteristics of the procurement data, including variable granularity and mixed-code entries, created “noise” that made it unstable. This led to a necessary pivot by adopting instead the Waste Concept as the initial reference point. Procurement data remained essential, but its role was redefined to function only after being cleaned and mapped to the categories established by the physical outputs.

Starting then from the Waste Concept, it was reasonable to develop a Waste Typology in order to organize outputs that would then be connected to the Material Concept. Likewise, this typology fed the prioritization matrix that eventually identified four main waste streams for focused analysis. With those priorities established, the effort was directed to recoding the procurement groups that matter for those waste streams instead of reclassifying the entire dataset. Then, standardizing CPV entries to the three-digit level and correcting misassignments produced the coherent procurement input that clustering could work with.

Clustering later allowed for the formation of material groups that reflected real campus outputs rather than artefacts of inconsistent coding. This was crucial as clustering unrefined data would have produced analytical noise rather than functional mass estimates. By linking them to the waste streams, it produced the necessary structure for a defensible proxy comparison. The alignment found in the results is therefore not a coincidence of the data, but a direct consequence of this systematic stabilization of both sides. The steps taken in this study were grounded in institutional decisions that are documented and explained throughout. Whether a comparable approach could be considered in other contexts would depend on their specific data conditions and regulatory environment.

6.3. Implications for the Scientific Community

The primary contribution of this research to the scientific community is addressing the transparency gap in the data preparation phase of Organizational Life Cycle Assessments. International guidelines such as the OEF guide acknowledge that O-LCA results are often not directly comparable across organizations because the methodological choices made during inventory construction remain unique to each study [15]. By documenting the full reasoning behind the reclassification of CPV procurement codes into physical waste categories and making each mapping step explicit, this work moves data preparation out of the background and into the analytical foreground. Future researchers could verify, challenge and reproduce the assumptions of any inventory built on this logic, rather than inheriting an unclear process that precedes the impact assessment phase.

A second contribution is the empirical and conditional validation of administrative procurement data as a legitimate primary activity data source for calculation-based inventories [20], [24]. The principle that environmental performance assessment depends on the choice of adequate raw data and reliable relationships between those data points is operationally demonstrated here rather than simply restated. Where the conditions of physical discreteness, auditable CPV-to-waste mapping and conversion factors grounded in validation benchmarks hold, procurement records can produce inventory estimates within a precision range appropriate for screening-level assessments. The conditional framing matters because it gives researchers a diagnostic rather than a blanket endorsement, clarifying when the proxy is structurally reasonable and when temporal or scope corrections are needed before results can be interpreted.

A third contribution is the empirically grounded asymmetry between short-life and long-life material flows, which is a generalizable finding for any researcher applying procurement-based methods in an institutional context [22], [24]. For consumables such as office paper, procurement and waste generation are more temporally aligned because purchase and disposal occur within more or less the same reporting cycle. Instead, for long-life assets such as IT equipment, the relationship inverts as a procurement-based estimate captures future waste potential rather than current disposal, and the temporal gap between purchase and end-of-life becomes a structural feature of the method that must be anticipated rather than treated as noise. The divergent results between paper and WEEE in this study are a direct empirical illustration of this. Researchers applying procurement proxies in other institutional settings can use this asymmetry to anticipate methodological performance before results are collected and choose the appropriate temporal correction strategy for each category.

Fourth, the Stream Logic presented in Chapter 2 gives researchers a specific instrument for making boundary decisions explicit before data collection begins [15], [30]. Prior studies have noted that unregistered fluxes and inconsistent documentation frequently lead to underestimating organizational environmental impacts, partly because exclusions are driven by data availability rather than deliberate attribution of responsibility [20]. The Stream Logic responds to this by classifying flows according to operational control, origin along the value chain and temporal residence, so that every boundary decision can be justified and documented. This transforms exclusions from implicit assumptions into a more auditable choice, which is particularly consequential in large, decentralized institutions where the same material can arrive through multiple institutional routes and data ownership is rarely self-evident.

Fifth, a connected methodological implication concerns the quality of the input data itself. The procurement dataset in this study is structurally hybrid as entries above the 40.000-euro threshold were coded by human operators with variable training, while smaller purchases, which represent the vast majority of records, were assigned codes through a predictive AI model trained on those same human-coded entries, whose classification consistency could not be assumed to be uniform across records. This means classification uncertainty is not incidental but inherent in the input side of any procurement-based environmental analysis at POLIMI and it propagates through the inventory unless explicitly managed [24], [43]. By addressing this through harmonization, representative manual correction and systematic flagging of ambiguous entries, this thesis demonstrates that metrological characterization of inventory data must be an active part of the method, not an afterthought. Making this uncertainty visible and tractable rather than burying it in aggregate outputs is itself a contribution worth exploring for the field.

In summary, these five contributions do not propose a new theoretical framework for O-LCA. They provide the scientific community with a documented set of activities that researchers working on university environmental assessment or organizational inventory construction can build on directly.

6.4. Implications for Practitioners

For procurement coordinators, sustainability practitioners and institutional managers at POLIMI and comparable universities, the outputs of this study provide a set of concrete and immediately usable tools.

The Waste Typology aligns directly with the university's Strategic Sustainability Plan, which targets the monitoring of 100% of the waste produced by the institution [3], [4]. By organizing municipal and special waste fractions into a single regulatory-aligned classification that specifies the appropriate administrative data source for each stream, the typology gives sustainability officers a structured scaffold to operationalize that target using data already existing within the institution [35]. A concrete early sign of its practical effect is that AMSA agreed to begin providing paper waste data separately following a specific request supported by this project. While AMSA-managed fractions remain the most difficult to attribute precisely because collection data is aggregated at the neighbourhood level, the typology has already begun to shape how data is requested and how collection is structured, confirming that clarity on a shared classification is a prerequisite for consistent ongoing monitoring.

The harmonization logic developed for the procurement dataset allows the administration to continue and extend this work without starting from scratch. The reclassification of CPV codes to the three-digit level, the correction of representative miscoded entries and the semantic matching rules linking purchase descriptions to waste-relevant categories were documented as repeatable steps rather than one-time manual interventions. Procurement coordinators could apply the same rules to future data cycles and extend the logic to additional waste streams as analytical capacity grows. For the streams analysed here, the dataset produced in this work already presents a baseline rather than an artefact to be discarded after the study concludes.

The material clusters produced for each waste stream are also relevant. They allowed for the exercise of translating procurement descriptions into physical categories that correspond to how waste is actually generated on campus. Rather than attempting to trace every individual purchase to a physical output, which is neither operationally feasible nor methodologically necessary, the clusters identify the procurement categories that account for the majority of potential waste mass in each stream, reflecting the widely endorsed principle that data collection efforts should concentrate on the small number of high-impact inputs that drive most of the relevant flows. For practitioners preparing a future O-LCA inventory, the clusters already indicate which categories to prioritize, where conversion factors have been established and how procurement descriptions can be translated into physical quantities. Beyond inventory work, the clusters also support more targeted Green Public Procurement decisions, since they make visible which specific product portfolios drive the most significant waste outputs, allowing the consideration of contract specifications to be directed at those categories first without waiting for a full organizational assessment.

A final practical consideration is that waste generation at a large research university is not continuous or evenly distributed over time. Through the meetings with the involved departments, repeated examples emerged of disposal events driven by laboratory cleanouts, office relocations and equipment replacement cycles, where a single event from one department could account for several hundred kilograms within a single recording period, as illustrated by a Physics department disposal that reportedly occurred in December 2023. For practitioners relying on annual waste figures for reporting or benchmarking, this event-driven character of flows means that single-year snapshots carry structural uncertainty that multi-year averaging can only partially resolve. The monitoring framework this study enables is therefore most reliable when read as a multi-year pattern rather than a single-year count, and when reported figures are accompanied by documentation of whether any exceptional disposal event occurred within the reference period to better understand the context. This is not a limitation specific to POLIMI but a structural feature of institutional waste generation that any practitioner applying this typology in a comparable context will need to account for from the outset.

6.5. Contextual Comparison with the University of the Basque Country

Among the institutions reviewed in Chapter 1, the University of the Basque Country (UPV/EHU) represents the most structurally comparable case to POLIMI, given its similar scale, public status and multi-campus nature layout. Bueno et al. [18] reported a comprehensive inventory of material inputs and waste outputs for the 2016 academic year covering 45.306 users. Before interpreting any numbers, three contextual considerations shaped the comparison. The reference years differ by approximately eight years (2016 vs 2024/2025), a gap that is particularly relevant for paper, where institutional consumption has declined markedly with digitalisation, and for WEEE, where the turnover cycles of devices have accelerated. Additionally, the two institutions differ in their staff-to-student compositions: POLIMI counts approximately 48.000 students and 3.100 staff [1], while UPV/EHU has roughly 39.360 students and 7.453 staff [18]. Since institutional procurement of IT equipment and office supplies is primarily staff-driven, this ratio matters when comparing input numbers.

In addition, the boundary scope differs in ways that affect the output side more than the input side, as the UPV/EHU inventory captures a broader range of waste flows that include canteen waste and materials brought by students onto campus, while

POLIMI’s waste measurements reflect the operationally managed streams described in Chapter 3.

With these flags in place, Table 6.1 presents the comparison for the three streams where at least partial data is available on both sides, normalised per institutional user.

Table 6.1: Comparison of POLIMI with UPV/EHU.

Stream	POLIMI Procurement Estimate (kg/yr)	UPV/EHU Material Input (kg/yr)	POLIMI Measured Waste (kg/yr)	UPV/EHU Waste Output (kg/yr)
Paper	118.852 (2,3 kg/user)	127.170 (2,8 kg/user)	121.463 (2,4 kg/user)	227.668 (5,0 kg/user)
WEEE	11.082 (0,2 kg/user)	*3.100 computers/year (not reported in kg)*	18.005 (0,4 kg/user)	24.443 (0,5 kg/user)
Hazardous waste	29.124 (0,6 kg/user)	*Not directly matching category found*	30.123 (0,6 kg/user)	64.648 (1,4 kg/user)

Table Note: POLIMI user base: approximately 51.500 (students and staff). UPV/EHU user base: 45.306. UPV/EHU figures extracted from Table 4 of the source study (Bueno et al. [18])

On the input side for paper, POLIMI and UPV/EHU landed at almost the same figure despite an eight-year gap between the two studies. That proximity is informative on its own because it suggests that institutional paper purchasing at universities of this scale converges around a similar operational baseline and that digitalization has reduced consumption meaningfully but not dramatically in absolute terms. On the output side, the gap opens sharply, which suggests a scope difference rather than a performance one. UPV/EHU’s output captures canteen paper, student-brought materials and mixed printed matter from common areas, none of which fall within POLIMI’s operational boundary established in earlier chapters.

For WEEE, the input side cannot be compared in mass terms because UPV/EHU reports computer equipment in units rather than kilograms. On the output side, the two institutions are much closer than for paper. The UPV/EHU’s slightly higher value is exactly what was expected from an institution with a larger share of staff, since WEEE generation can be considered primarily staff-driven.

For Hazardous Special Waste, the output gap is the largest of the three streams. Two factors could explain most of it. UPV/EHU’s inventory covers hazardous streams comprehensively while POLIMI’s was scoped to two specific output groups, so the comparison is not fully symmetric on the output side. Furthermore, UPV/EHU’s faculty composition includes a higher concentration of chemistry, pharmacy and intensive laboratory programmes, which are structurally heavier generators of laboratory waste than POLIMI's engineering profile.

Across all three streams, the differences come from scope, year and institutional composition rather than from anomalies in the data. Because higher-education waste inventories do not yet follow harmonized boundary definitions, this kind of unpacking is always needed before comparing institutions. The UPV/EHU study itself notes this gap [18], and structured inventories could help reduce it.

6.6. Conclusions

This study demonstrated the feasibility of using procurement records to estimate material waste generation at POLIMI within the established Operational Perimeter. By investigating four distinct waste streams, the work answered whether spending data can serve as a reliable proxy for physical flows in a decentralized university environment. The empirical evidence confirms that this proxy is indeed valid when specific conditions are met, particularly the existence of physically discrete categories and auditable mapping rules. Estimates for Bulky Waste, Municipal Paper and Hazardous Special Waste showed high consistency with the actual measured values. In contrast, the deviation observed in the WEEE results proved analytically significant, as it provided useful insights that reflected the complexity of this waste stream in an organizational context.

The methodological process followed a four-step sequence to ensure the results were defensible. This involved defining an Operational Perimeter, cleaning and harmonizing procurement data at the three-digit level, mapping the records to the Waste Typology, and validating the findings against measured weights. This systematic approach transformed fragmented administrative records into a structured baseline for environmental monitoring.

Throughout this activity, the study produced two primary data structures: a unified Waste Typology organizing 14 fractions by management channel and regulation; and a harmonized procurement dataset, consolidating five years of activity into CPV groups that enabled the performance of the input-output exercise in this study.

For the scientific community, this work documented the transformation logic required to bridge the gap between institutional spending and inventory inputs, while for practitioners at POLIMI, the study provided the tools and the initial guide for the roadmap necessary to extend this analysis to Energy, Water, and Land.

The contextual comparison with UPV/EHU added an external validation dimension by showing that POLIMI's figures, once differences in scope and institutional composition were accounted for, fell within the range that a structurally comparable institution with a more comprehensive inventory reported for three items inside the Material and Waste Concepts, supporting the credibility of the baseline produced here.

Ultimately, this thesis served to demonstrate that institutional data can be successfully reorganized to support sustainability monitoring, providing a documented baseline applicable to future university assessments.

6.7. Limitations

With the main findings drawn, it is important, both for transparency and comparable institutional context, to keep the limitations in mind for any future development or reference of this study in other assessments.

One primary challenge arose from the inherent characteristics of the procurement records, including uneven granularity of CPV codes and the use of service codes for goods. These peculiarities were addressed through actions such as the three-digit harmonization and manual cleaning, targeting the most relevant entries for the study and keeping the most defensible core of the dataset for the input-output matching evaluation.

A related constraint concerned the structural reliability of the dataset itself, resulting, as explained above, partly from the manual assignment of CPV codes by untrained operators and partly from an AI model that was trained on those same entries. Classification uncertainty is structural rather than incidental to the input data and was addressed in this thesis through the harmonization steps applied but could not be eliminated entirely.

Another limitation emerged from the centralized nature of the university's procurement system. Although the analysis filtered to exclude the "Territorial Poles", some entries were later found to correspond to them and even to residences. This reflected the structural difficulty of isolating flows by physical location when all purchases were recorded under a single institutional accounting system.

A further constraint related to the conversion from monetary to mass. The conversion factors applied were based on institutional consensus and market research rather than direct weighing of every item. While future accuracy could be improved with supplier weight data, the university does not yet collect this information systematically. Hence, this approach currently remains the most reliable way to estimate the flows.

Additionally, a structural asymmetry also existed between inputs and outputs. As discussed in Section 6.1, the procurement side captures only institutional direct purchases, while the waste output covers everything that physically left the campus regardless of origin, an imbalance that was anticipated in the Operational Perimeter and does not invalidate the findings. Less obvious but equally real is an incompleteness on the output side itself, as certain contractor-managed streams, for which the contractor holds legal responsibility for disposal, appear in POLIMI's waste records only as exceptions rather than as complete flow data. For Hazardous Special Waste specifically, the output quantities may also carry a slight upward bias because chemical containers are weighed together with their contents at disposal, a detail already noted in Section 6.1 that the available data could not correct for.

Temporal mismatch between information from both sides also shaped the analysis. Procurement data covered 2020 to 2024, while the waste records were available mainly for 2023 and 2024, with partial coverage of 2025 for specific streams. For this reason, a yearly average approach was taken to make the data functionally comparable, which helped smooth variation but could not fully resolve timing differences, particularly for long-life goods, as discussed in Section 6.1. A further complication is that waste generation tends to be episodic rather than continuous, with concentrated disposal events tied to equipment renewals, laboratory cleanouts or relocations that can shift annual totals significantly without a corresponding change in procurement for that same year.

An additional observation concerned the completeness of the 2024 procurement records. Because the dataset was provided at the beginning of 2025, the Procurement Department noted that the 2024 entries might not yet have reflected the full year's purchasing activity. However, the average annual procurement estimate remains appropriate, as it smooths year-to-year variation and limits the influence of any single year's reporting completeness.

A final structural constraint, which compounds the temporal mismatch described above, is that POLIMI actively encourages repair, reuse and internal redistribution before replacement [44]. This means that assets can remain in circulation well beyond their nominal purchase cycle, further widening the gap between when items are procured and discarded. The proxy implications of this are discussed in detail in Section 6.1 in the context of WEEE.

6.8. Future Next Steps

The findings of this study open paths for follow-on work at POLIMI that are not generic research agendas but concrete activities the Sustainability Office, the Procurement Department and the Waste Management Department could advance together, some of which are already within reach.

Institutional Actions

The most immediate action involves integrating the sensor outputs from the Nando project [45] directly into the Waste Typology structure developed in this thesis. Launched in 2024, Nando equips campus bins with sensors that recognize and record waste [45], representing the latest step in a long institutional effort to compensate for data gaps through smart infrastructure [46], [47]. This tradition dates back to the PIC system (*Piattaforma per Contenitori Intelligenti*) developed in 2003 by the Department of Mechanics, which pioneered real-time weight and volume monitoring to address the university's structural data fragmentation [47]. Integrating these sensor-based inputs as a source of continuous data that feeds directly into the Waste Typology structure would move the AMSA branch of the inventory from estimated to measured. This branch currently remains the most difficult fraction to detail precisely since AMSA reports POLIMI's waste together with surrounding households in the area.

A second concrete direction involves making product weight a standard field in procurement documentation. Suppliers already include this information in product datasheets, but it does not currently travel with the purchase record inside POLIMI's systems. Requesting this field in future supply contracts requires no new infrastructure and would progressively replace the estimated conversion factors used in this study with real mass data. It would also enable a prospective use of the methodology developed here, where planned procurement for large and non-routine purchases such as full laboratory equipment renewals or major office refurbishments could be translated into an anticipated waste signal before the disposal event occurs, giving the Sustainability Office and the Waste Management Department a planning window to pre-negotiate contracts or engage circular economy alternatives before the waste materializes.

A third direction was raised directly during discussions with the Waste Management Department and concerns the economic framing of certain waste streams. Paper, recovered metals from dismantled furniture, and inert materials from laboratory testing activities carry established recovery value in current markets, yet they are currently managed primarily as a disposal cost. The typology and the material cluster structure produced in this study could support a different reading without requiring additional data collection. Making the physical composition of each waste stream explicit and linking it to procurement categories makes it easier to identify where investment in separate collection or material recovery contracts would be justified, and to direct contract specifications toward more durable or recoverable products where the category and the market allow it. This reframing also connects directly to POLIMI's active institutional commitment to repair, reuse and internal redistribution before replacement [44], offering a data-backed pathway to operationalize that commitment at the procurement stage rather than at end-of-life. As data quality improves, the prioritization matrix already offers a clear path for extending the analysis to additional waste fractions; and the five Concepts outline the scope for future work on Energy, Water, and Land, using the same Operational Perimeter and Stream attribution reasoning applied here.

Recommended Future Research Directions

To advance this academic framework, some ideas are presented below to systematically address open topics pointed out by this study.

Regarding WEEE at POLIMI, the temporal mismatch between IT procurement and WEEE disposal remains a critical point of inquiry, as this asset lag creates a significant gap that limits the direct proxy comparison. To address this gap more directly, future investigations could focus on the validation of a life cycle timing model. POLIMI's ICT asset registry and the procurement dataset produced here provide the input needed to test whether applying a five-to-seven-year lag to digital procurement data meaningfully improves alignment with measured disposal volumes. The scope is contained and the data is institutional. The natural collaborators would be the ICT, Waste Management and Procurement Departments.

Another essential area of research focuses on developing green public procurement specifications for priority waste categories at POLIMI. The 2022 Sustainability Report shows that while 14 CAM (*Criteri Ambientali Minimi*) criteria are formally applied, the average sustainability score in procurement tenders is 17 out of 100 [3]. The CPV groups and the material clusters per stream produced in this thesis would represent the input needed to translate that gap into contract-level action. Examples could include requiring modular design and take-back for furniture contracts, and a minimum declared product lifespan for IT contracts. Researchers could take the top clusters and translate them into concrete, verifiable specifications per category. This connects directly to the "*Sostenibilità degli acquisti Cantiere*" in the Strategic Plan [3] and to the resource recovery reframing already present in this section.

Furthermore, a significant broader objective points towards a complete Organizational Life Cycle Assessment at POLIMI, by building a comprehensive inventory foundation across the five Concepts. This thesis demonstrates that a procurement-based material and waste inventory is feasible at POLIMI when the right context is in place. The logical next step would be to extend this study to the remaining Concepts such as Energy, Water, and Land, using the same Operational Perimeter and Stream attribution logic so that together they constitute the Life Cycle Inventory phase of a full O-LCA. One or two of those Concepts could be selected to apply a similar data strategy documented here and produce an inventory component that sits alongside the material-waste mapping already built. The cumulative output across all Concepts would give POLIMI the structured, auditable inventory that a full O-LCA under ISO 14072 currently lacks and would position the Sustainability Office and the POLIMI LCA Network to carry out the impact assessment phase that follows.

Finally, future investigations could explore the transition from procurement clusters to environmental impact scores by applying economic input-output LCA models to POLIMI's spending data. Economic Input-Output LCA (EIO-LCA) estimates environmental impacts by multiplying expenditure data with sector-level emission and resource intensity coefficients taken from national input-output tables, such as the US EIO-LCA model from Carnegie Mellon or the EXIOBASE database used in Europe. Clemson University has already shown that this approach works in a university context by using expenditure data where physical quantities were missing [20]. The CPV groups developed here, already organised by material type and waste stream, can be matched directly to EXIOBASE or NACE sectors. Researchers could use this to run EIO-LCA calculations and produce an expenditure-based environmental impact profile of POLIMI's procurement. This would extend the analysis from waste flows to broader impact categories such as carbon emissions, water use and resource depletion. It would also form a direct bridge between the inventory work completed here and the impact assessment stage required in a full O-LCA [15].

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A Appendix A

Below are presented the main Excel documents that were used for the development of this study. All files are also available in the OneDrive shared folder named: Thesis - July 2026 and included as separate files at the time of submission.

A.1. Procurement Source Dataset Excel: "acquisti_POLIMI_13_25_CPV"

It contains the raw procurement dataset given directly by the Procurement Department and better described in Section 4.1. Includes all original records before any cleaning, harmonization, or reclassification.

A.2. Final Procurement Output Excel: "FINAL_Paretos Analysis and Modified Dataset"

It contains the following information:

- Dati_v33: This sheet shows the final harmonized procurement dataset, representing the cleaned and reclassified version of the original file provided by POLIMI's Procurement Department, as described in Section 4.3. It consolidates 19.457 records into 209 three-digit CPV groups covering 2020 to 2024 and serves as the primary input for all stream-level analyses and the rest of the sheets.
- Classification matrices: (MP|NMP|TAD, B|NB|TAD, WEEE|NW|TAD, HSW|NHSW|TAD) These sheets show the data separated into the three groups after initial cleaning, showing the confirmed stream items, the ones excluded and a last category for cases that require more information for a clear decision.
- Pareto analysis sheets: (MP PARETO, B PARETO, WEEE PARETO, HSW PARETO): These sheets rank the cleaned records already grouped into clusters,

so they no longer use the full list of individual records. The ranking is based on procurement value and also includes the comparison with waste data.

A.3. Waste Data Sources (Original Excel Files Only)

These are the three raw files provided by the Waste Management Department. They constitute the waste-side input used in Sections 3.3 and 3.4.

- "Tabella rev 3_ L": Refers to Source (i). Internal reporting sheet covering several waste fractions by collection channel (Jul-Dec 2024).
- "Raccolta Dati_": Refers to Source (ii). Administrative reports covering special waste (2023) and municipal fractions (Jul-Oct 2024).
- "Pesatura_carrellati_2025": Refers to Source (iii). Operational measurements of Paper Waste (July-Dec 2025).

A.4. CPV Reference Excel File - "CPV - Full"

This Excel file was built by the author in Jupyter using the official European Union Procurement list [37]. It contains 8-digit codes without trailing zeros which was cross-referenced to append official English descriptions and structural hierarchy tiers to the already procurement data existing inside A.1. to finally obtain Dati_v33 (inside A.2.)

Below in Table A.1, a summary to clarify the connection.

Table A.1: Summary of sources.

Component	Source
acquisti_POLIMI_13_25_CPV	Raw procurement source
CPV_FULL	External reference for CPV structure
Tabella rev 3_L	Waste Source (i)
Raccolta Dati_	Waste Source (ii)
Pesatura_carrellati_2025	Waste Source (iii)
FINAL_Paretos Analysis and Modified Dataset	Final processed procurement output

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This work also benefited from people who helped shape it directly. Prof. Alessandro Perego proposed the project and provided the conceptual framework that gave the research its starting point and direction. Dr. Federica Costa's guidance kept the analysis grounded, and I am grateful for both her constant feedback and the professional advice she shared during our meetings. This study would not have been possible without POLIMI's relevant administrative departments, whose openness ensured the results stayed connected to real everyday practices.

Lastly, to anyone who reaches this page with their own thesis still ahead: it is never too late to pursue what matters to you. What stays with you in the end is not the result, but the certainty of having given your best to it, and that feeling is something no grade can take away.