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Analysing material and embodied environmental flows of an Australian university — Towards a more circular economy

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ABSTRACT

Humans are extracting and consuming unprecedented quantities of materials from the crust of the Earth. Contributing to this consumption, university campuses require large amounts of materials to operate. This offers opportunities for the implementation of circular economy principles that optimise material use and demonstrate best practice to future generations of decision makers, globally.

This paper uses the Parkville campus of the University of Melbourne as a single revelatory case study to quantify its material flow for 2017. We use extremely disaggregated procurement data of 11 555 purchases of materials, mapped against 189 different material archetypes to estimate material inflows. Material outflows are sourced directly from the waste management contractor of the University. We also quantify the embodied energy, water, and greenhouse gas emissions of all inflows, using environmentally extended input-output analysis.

Results show that procurement-related inflows tend to represent a small share (~4%) of the total material flows (2 280 Gg), but result in significant environmental effects due to the nature of the materials (e.g. electronics, cabling, photovoltaic panels, furniture, etc.). The modelled procurement-related purchases result in 22 587 GJ of energy, 1 477 GgCO_2e of greenhouse gas emissions and 30 891 kL of water, and 3.46 MAUD in cost, annually. Yet, the majority of material flows on campus tend to be generated by non-procurement-related drivers, notably food and food packaging waste resulting from retail on and off campus. Based on these findings, the paper recommends a series of actions that universities and large organisations can adopt to transition to a more circular economy.

1. Introduction

Global resource consumption is increasing at unprecedented levels (Schandl et al., 2016; Wiedmann et al., 2015), driven mostly by cities (Krausmann et al., 2017). For instance, humans used ~585 EJ of primary energy in 2017 (IEA, 2018) and extracted ~70 billion tons of raw materials in 2010 (Schandl et al., 2016). At this rate, a significant number of natural resources, notably metal ores, are set to be exhausted in the coming decades, such as copper, silver, gold and other metals (Graedel and Nassar, 2013). In response to this consumerist pattern that is driving resource depletion, there have been calls to transition from a linear to a more circular economy (Ellen McArthur Foundation, 2019; Tukker, 2015; United Nations, 2015), where waste is considered as another material flow that can be recirculated in the economy, instead of being sent to land-fill. This transition can significantly limit the amount of discarded materials, create value (and jobs) and reduce environmental effects associated with both the extraction and manufacturing of new materials as well as their processing and disposal.

Universities have a critical role to play in helping support the transition to a more circular economy. This role is multi-faceted, including educational, research and leadership aspects. As innovative and progressive hubs that employ a large number of individuals, own significant property, and require significant material inflows (and outflows) to operate, university campuses present ample opportunities as living labs for a more circular economy, were guidelines and experiments can be applied and tested before they are scaled-up.

There has been increased interest from universities in improving the environmental performance of their campuses, illustrated by the number of signatory Universities to the "Talloires Declaration" (ULSF (Producer), 2019), membership of the International Sustainable Campus Network (https://www.international-sustainable-campus-network.org/membership/iscn-member-directory) and participants in

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the Association for the Advancement of Sustainability in Higher Education (AASHE) Sustainability Tracking, Assessment & Rating System (STARS) program (https://reports.aashe.org/institutions/participants-and-reports/). Many institutions pursue actions that could support a circular economy (e.g. reducing the life cycle energy demand and greenhouse gas emissions (Leon et al., 2018), recycling (Armijo de Vega et al., 2008; Kelly et al., 2006), purchasing products with recycled content, and furniture reuse). Yet, very few universities have actually analysed their material flows on campus comprehensively to identify issues and opportunities to transition to a more circular economy. This is the first step to implement a circular economy on campus, as highlighted by Mendoza et al. (2019).

One of the most prominent existing studies about material flow analysis on a university campus is the study by Lopes Silva et al. (2015), focusing on the Universidat Autònoma de Barcelona, Cataluña, Spain. In their study, Lopes Silva et al. (2015) quantify the overall metabolic rate of the university campus, across energy use, water use, greenhouse gas emissions, land-use and material use, covering both direct and indirect requirements. Their material flow analysis comprises four material categories: food, land-use (as in clay extracted from the ground), paper and other materials which include packaging, organic matter, glass and laboratory equipment. However, their approach to quantify material flows relies heavily on averages and extrapolations. For instance, food inflows use an average daily consumption per capita and the total number of users on campus. The 'Other materials' category is based on mass balances issued from waste auditing. The land-use flow is based on cubic meters excavated. Only the inflow of paper is measured using on-site data. These observations are based on what is reported in the journal article as no detailed data is provided alongside the journal article.

In light of the above, there is a critical need to provide the evidence base to transition universities and large organisations to a more circular economy, notably by providing very detailed accounts of their material flows. This will provide the background information that can help inform the implementation of circular economy strategies.

1.1. Aim and scope

The aim of this paper is to quantify the material flows and associated embodied energy, water, and greenhouse gas emissions through a university campus in order to evaluate the potential of different circular economy strategies. The Parkville campus of the University of Melbourne is used as a case study.

The study focuses on material inflows that are associated with the university procurement for the Parkville campus, where the majority of the University staff and students are based. This focus is to provide a detailed analysis of university purchases, their embodied environmental effects and potential for circularity. We considered all waste outflows from the campus via the waste management processes of the university, including waste resulting from university purchases as well as waste from other sources, such as student and staff food and beverage consumption, retail tenants on campus, and others. The scope of the study is depicted in Fig. 1.

Section 2 describes the modelling approach including a justification and description of the case study, data sources, quantification algorithms and investigated circular economy strategies. Section 3 presents the results and Section 4 discusses them, proposes circular economy strategies and presents the limitations before concluding in Section 5.

2. Modelling the material flows and associated embodied environmental flows of a university campus

This section provides all the details associated with the research design and modelling approach. Firstly it justifies the use of a case study approach and the choice of the case study before presenting the overall modelling approach and providing details about each step, in terms of choice of method and quantification.

2.1. Case study description: the Parkville campus of the University of Melbourne

This paper adopts a single case study approach as its main research method. This is because the system that is studied (material flows on a university campus) is common but data is very hard to obtain and is often confidential, making the case study critical and revelatory in nature, as described by Yin (2018, pp. 49–50). In addition, the focus of the study is relatively novel and there are no existing datasets, containing consistent information on a large sample of the population (i.e. large universities and corporations) to be readily used.

When adopting a single case study approach, the case needs to be chosen carefully to be representative of the population that needs to be studied in order to maximise the external validity (extrapolation) of the results (Fellows and Liu, 2015; Yin, 2018). In this case, the population studied comprises large higher education institutions in Australia. A significant body of universities within this space is the Group of Eight (Group of Eight, 2019), representing the eight top universities in Australia from an international ranking perspective and grouping most of the oldest higher education providers. The Group of Eight also represents some of the most resourceful institutions in Australia, which attract more than 70% of all government research funding schemes and graduate more than 25% of all students (Group of Eight, 2019). Within the Group of Eight, we chose the University of Melbourne based on its key characteristics in terms of number of students, number of staff, and most importantly the number of students per staff as a normalised metric. We obtained data on all Australian higher education providers from the Department of Education (2018) of the Australian Government.

The University of Melbourne is the second largest institution in Australia in terms of number of students and staff and has the largest research budget (The University of Melbourne, 2017). Its number of students and staff is of the same order of magnitude as all other institutions in the Group of Eight. Its students per staff ratio of 5.82, a relative measure to normalise university size, is very close to the mean (5.63) and the median (5.62) of the Group of Eight (Z-score of 0.28 σ). When compared to the students per staff ratio of all higher education providers in Australia with 15 000 students or more ($N = 27$, $\mu = 7.71$, median = 7.62, $\sigma = 1.7$), the Z-score of the University of Melbourne shifts to $-1.1\ \sigma$ but is still representative of the population. In light of these attributes, the University of Melbourne, and its main Parkville campus are a suitable choice as a case study in the Australian higher education sector. The fact that we had access to extremely detailed procurement data from the University of Melbourne reinforces its choice as a revelatory case study to conduct a material flow analysis of a university campus (Yin, 2018, p. 50).

The main campus of The University of Melbourne caters for over 50 000 students and is located in Parkville, Melbourne, just North of the central business district. The campus covers 360 000 m^2 of land and includes a number of buildings with a total indoor gross area of 722 960 m^2. This campus is a traditional and representative university campus, including multiple and diverse faculties, food and beverage stores, gardens and parks and a mix of old and new buildings. The main characteristics of the Parkville campus and the University of Melbourne, which is depicted in Fig. 2, are summarised in Table 1.

2.2. Overall modelling approach

The modelling approach can be divided into five main steps, as depicted in Fig. 3. These steps are described individually below.

1. Establishing material inflows (see Section 2.3);
2. Calculating embodied energy, water and greenhouse gas emissions associated with inflows (see Section 2.4);

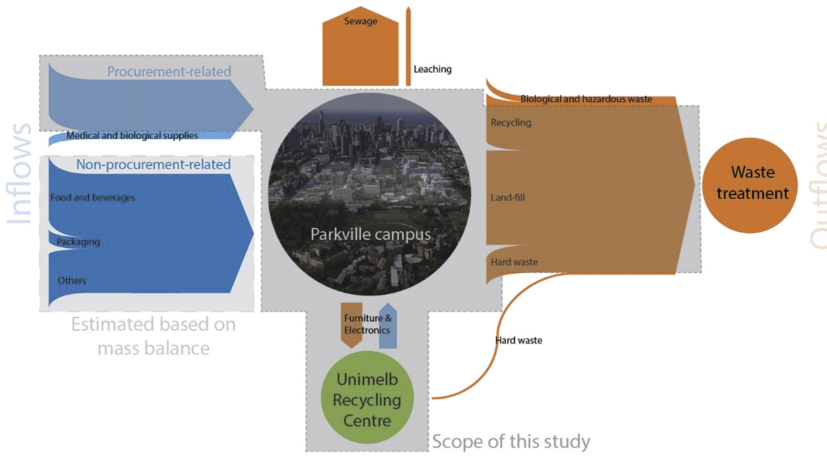

Fig. 1. Scope of the study in terms of coverage of material flows. Note: arrow thicknesses are indicative only and are not representative of actual mass flows.

3. Compiling material outflows (see Section 2.5);
4. Combining all data into an integrated material and embodied environmental flows analysis (see Section 2.6); and
5. Generating the results and identifying circular economy opportunities.

This approach relies on four distinct sources of data: university procurement data for material inflows, university waste data for material outflows, a range of sources (e.g. manufacturer product page, procurement details, etc.) to determine material archetypes and environmentally extended input-output data to quantify embodied environmental flows associated with material inflows.

2.3. *Quantifying material inflows*

Material inflows on the Parkville campus are derived from the university procurement data. Data from 2017 were chosen as they were the most recent and complete to date. A total of 406 527 transactions documented the university procurement for 45 account types, representing a total of 277 897 353 AUD. For each transaction, 51 fields were included, such as: budget division; supplier id; fiscal period; Australian Dollar amount; invoice amount; quantity invoiced; unit price; source; purchase invoice number; purchase order number; product category; vendor type; account name; invoice description; supplier name; merchant name; and description. This resulted in 15 338 729 data points which include all purchases that might have resulted in a material inflow, based on the expert opinion of the university procurement team. The data then needed significant processing and filtering to identify transactions that reliably resulted in a material flow. Issues of contamination (transactions with wrongly attributed fields) had to be manually corrected. We adopted a safe position where in the

Table 1
Main characteristics of the Parkville campus and the University of Melbourne, Australia, as of 2017.

Characteristic	Value
Campus Area	360 000 m^2
Internal gross area of Campus Buildings [a]	722 960 m^2
Total students enrolled	50 270
Academic staff	4 429
Professional staff	4 110
Total staff	8 539
International Students	39.8%
Total Underlying Operating Income	2 274 000 AUD
Total Underlying Operating Expenditure	2 248 000 AUD
Total Academic and Professional salaries	1 185 000 AUD

Note: All figures from The University of Melbourne (2017), except [a] based on The University of Melbourne (2019).

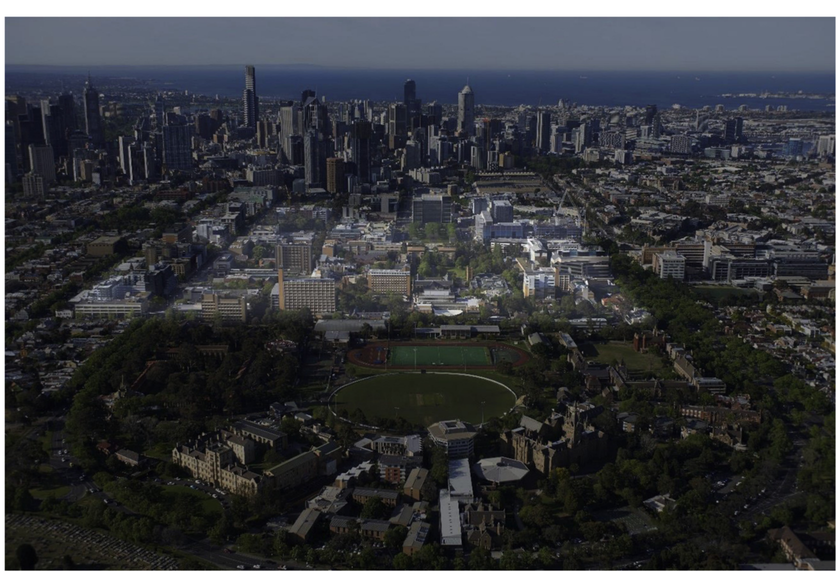

Fig. 2. Aerial view of the case study Parkville campus of the University of Melbourne (highlighted).

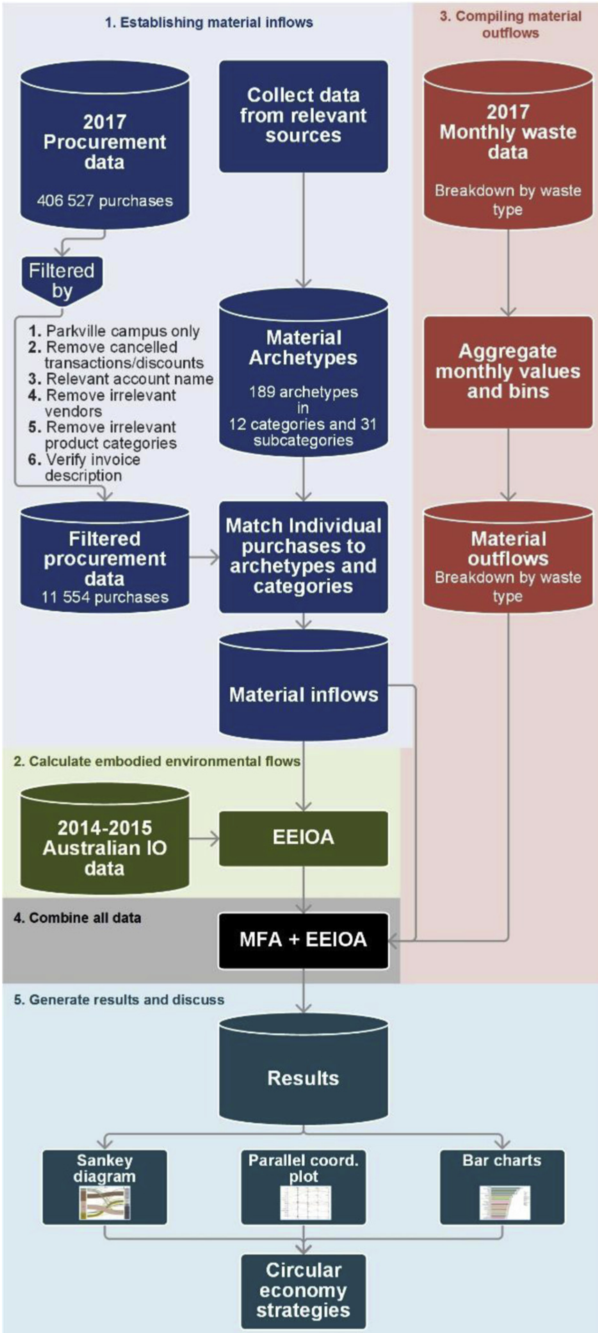

Fig. 3. Overall modelling approach and scope.

absence of enough metadata to characterise a transaction and an associated material flow, we did not include that material flow. This results in a more conservative estimation in which we are more confident about the minimum procurement-related material inflows of the campus, compared to a more speculative approach.

As depicted in Fig. 3, we applied six main filters to the original **406 527** transactions. These are listed and detailed below:

1. Include transactions that apply to the Parkville campus only. This retained **345 413** transactions.

2. Filter remaining transactions by account type name. We excluded accounts based on the service-oriented nature of the services or because the potential material outflow that they might yield was not deemed appropriate to be re-used, recycled (e.g. from the account *Laboratory consumables*). This process filtered out inflows that result in hazardous waste (discussed in Section 4.3). This filter retained **165 329** transactions. The accounts that were excluded are:

a. Advertising and promotion;
b. Animals and animal provisions;
c. Biological materials;
d. Chemicals;
e. Domestic travel (accommodation and incidentals) on university business;
f. Domestic travel (transport) on university business;
g. Garbage and refuse removal;
h. Hire of equipment;
i. Hire of venue or facilities;
j. Ionising radiation;
k. Laboratory consumables;
l. Postage, freight and cartage;
m. Software and online services; and
n. Subscriptions and membership.

3. Remove irrelevant vendors types (see below), which retained **163 887** transactions.

a. Chemicals;
b. Hire of equipment;
c. Motor vehicles;
d. Rentals;
e. Postage and mailouts;
f. Medical supplies; and
g. Travel agencies.

4. Remove cancelled transactions (i.e. identical transaction with a positive and negative cost value) as well as discounts. This retained **34 833** transactions (note the large number of such transactions).

5. Remove irrelevant product categories (see below), which retained **32 995** transactions.

a. Medical supplies;
b. Chemicals unrestricted;
c. Postage freight and cartage; and
d. Non-categorised postage and freight.

6. Filter manually, transaction by transaction, using the invoice description and excluding wrongly allocated or contaminated transactions. This retained **11 555** material transactions.

The total value of the **11 555** material inflows represented a total value of **3 466 332 AUD**. The mass associated with each transaction needed to be calculated in order to establish the procurement-related inflows in kilogrammes.

We used an archetypes-based approach to model the material inflows associated with transactions. Using archetypes is an efficient manner to streamline the modelling. Instead of attempting to determine the mass associated with each transaction by identifying which items were bought and what is their mass, we create a more generic archetype that is representative of a type of product (e.g. a desk) that we allocate to desk purchases. This approach has been successfully used for material flow modelling of built stocks, where thousands of buildings are considered (Fishman et al., 2016; Stephan and Athanassiadis, 2017, 2018; Tanikawa and Hashimoto, 2009). In this case, we defined 189 individual archetypes, across 16 categories and 48 sub-categories. For each archetype, we included 50 fields such as: archetype name (e.g. book), category (e.g. stationery), mass (e.g. 0.44 kg), a breakdown by multiple material types and all sources and assumptions. For each archetype, we sourced the information directly from the supplier website, where available. If this was not possible, we used information from a different supplier for a very similar product to approximate the archetype mass and material breakdown where available. In more than 80% of cases, we were able to identify the exact item purchased from university suppliers and the exact mass from third party suppliers that provide that information. Archetypes also included environmental information as discussed in Section 2.4.

The total material inflows associated with university procurement data for a particular campus and year are calculated as per Eq. (1) below. The calculation consists of matching a transaction to an archetype, multiplying the quantity of items in the transaction by the mass of the archetype and summing over all transactions.

$$PMIF_{c,y} = \sum_{t=1}^{T} M^{\mathrm{A}}_{t,c,y} \times Q^{\mathrm{A}}_{t,c,y} \tag{1}$$

Where: $PMIF_{c,y}$ is the procurement material inflows of campus c for year y in Gg (kt); $M^{\mathrm{A}}{}_{t,c,y}$ is the mass of archetype A associated with transaction t for campus c in year y, in Gg (kt); and $Q^{\mathrm{A}}{}_{t,c,y}$ is the quantity of archetype A associated with transaction t for campus c in year y.

It is important to note that when quantities were not specified in a transaction, these were derived based on the total transaction cost and unitary prices provided. In some cases, reported quantities in the procurement data were erroneous. This resulted in extremely skewed material inflows. We manually corrected the quantities for these transactions by sourcing the correct unit price from the supplier and correcting the quantities purchased by dividing the total transaction value by the unit price. Corrections were made for transactions involving 48 out of the 189 archetypes (25.4%).

Material inflows not associated with university procurement (e.g. food scraps from food and beverage retail on university grounds) where simply derived from material outflows (see Section 2.5) to maintain mass balance. These are not disaggregated but are added only for completeness.

2.4. Quantifying embodied environmental flows associated with material inflows

To better inform decision-making for a more circular economy, it is important to consider the environmental effects of material flows, beyond mass alone. This can be done by quantifying the embodied environmental flows associated with each material flow.

In this case, the procurement data that are used as the basis for the calculation of inflows contain detailed cost information. This is ideal for the use of environmentally extended input-output analysis to estimate the environmental effects associated with each transaction. Input-output analysis is a top-down macroeconomic approach that uses bi-dimensional tables representing sectors of an economy. Input-output analysis covers recorded transactions across the entire economy. It can provide a comprehensive estimate of the total environmental effects associated with a purchase (Majeau-Bettez et al., 2011).

Leontief (1970) first developed an approach to combine sectorial economic transactions with environmental data. The combined matrix can be used to derive the total environmental intensity of a particular sector, e.g. water: L/currency unit. These sector-based intensities can be used to quantify the environmental effects of a product or purchase, based on its cost and the sector to which it belongs. The first study using environmentally extended input-output analysis was conducted by Isard and Romanoff (1967) and this technique has been used hundreds of times since in multiple studies around the world.

In this study, we used input-output data for 2014 that was extracted from the Industrial Ecology Virtual Laboratory (Manfred Lenzen et al., 2014), at 114 sectors resolution, in basic prices. We used the extended version of this dataset, including capital as four additional sectors, namely: ‘biological resources’ (livestock), ‘construction’, ‘machinery and weapons’ and ‘IP products’ (software, etc), using data from ABS, 2016, 2018 and the augmentation method described in M. Lenzen and Treloar (2004). We also used environmental satellites for energy, greenhouse gas emissions and water developed in Stephan et al. (2018) for the same financial year, and based on DIIS (2016); DEE (2019) and ABS (2017), respectively.

We matched each of the 189 archetypes (e.g. paper ream) with the input-output sector to which it belongs (e.g. Pulp, Paper and Paperboard Manufacturing) and extracted the relevant environmental intensities for energy, greenhouse gas emissions and water. Using the expenditure for each transaction, we converted the AUD value of the transaction to the relevant embodied environmental flow by multiplying the expenditure by the relevant environmental intensity, as per Eq. (2). We adjusted the prices using a compounded inflation rate of 4.8% between 2014 and 2017. This enables us to quantify the environmental effects associated with material inflows and to understand better the potential repercussions of circular economy strategies, across multiple environmental indicators, beyond material mass and financial terms.

$$EEFPMIF_{c,y} = \sum_{t=1}^{T} X_{t,c,y} \times EEI^{\mathrm{S,A}}_{t,c,y} \tag{2}$$

Where: $EEFPMIF_{c,y}$ is the embodied environmental flow for procurement material inflows of campus c for year y in environmental flow units (e.g. GJ for energy); $X_{t,c,y}$ is the expenditure of transaction t for campus c in year y, in currency units (e.g. AUD); and $EEI^{\mathrm{S,A}}{}_{t,c,y}$ is the embodied environmental intensity of sector S to which archetype A belongs and which is associated with transaction t for campus c in year y, in environmental flow units per currency unit (e.g. GJ/AUD for energy).

It is important to note that environmental intensities are calculated using basic prices while the expenditure used to quantify embodied environmental flows includes margins. That means that the total environmental effects might be slightly overestimated. Given the errors associated with environmentally extended input-output analysis (Manfred Lenzen, 2000), this is deemed satisfactory for the scope of this study, the main aim of this environmental assessment being to identify hotspots and critical material flows. The sensitivity analysis in Section 3.1 provides a detailed evaluation of the repercussions of uncertainty on embodied environmental flows results.

2.5. Quantifying material outflows

Material outflows on the Parkville campus are based on waste statistics on campus. We obtained detailed monthly data for 2017 from the waste management contractor for the campus. These data provide a breakdown of waste collected on campus, by bin type (i.e. general waste or recycle bin), as well as hard waste. We also used a waste audit conducted in March 2017 that provided a breakdown of waste bins, by waste type. We used that breakdown as a proxy across the year, to further divide outflows into relevant streams. In summary, we used six waste types to characterise outflows (including hard waste), namely: metal, timber, plastic, rubbish, paper and cardboard, green, comingle and general waste. Hazardous waste outflows were not considered as the scope for circular economy strategies are extremely limited, due to the nature of this outflow as well as its small total mass.

In addition to waste statistics, we used in-house data on furniture reuse and recycling to direct a part of the furniture outflow to the the University of Melbourne Reuse Centre. Furthermore, gardening soil was categorised alone as it remains on campus and is subject to leeching or absorption over time.

2.6. Combining all data to conduct the material and embodied environmental flows analysis

Once the inflows, their embodied environmental effects, and outflows were all quantified, we combined all three datasets to conduct the analysis. Material inflows and outflows were linked based on the archetype category (we developed a small concordance matrix to allocate material inflow categories to relevant outflow categories). For materials that stay longer than one year in the in-use material stock of the campus, we did not account for their outflow during 2017. This also means that some material outflows from procurement-related inflows in 2016 could also be present in the waste data that we collected, this is further discussed in Section 4.3. We conducted the embodied environmental flows analysis of procurement inflows in parallel.

2.7. Data availability

We strongly believe in data transparency and in the reproducibility of results. In accordance with best practice recommendations from the field of Industrial Ecology (Hertwich et al., 2018), we made all relevant supporting data available through Figshare[1] (Stephan et al., 2019). These data include:

- The 11 555 transactions representing procurement material inflows, along with relevant metadata; and
- The detailed description of each of the 189 archetypes used; and
- Material outflows data, by type.

The input-output data used, which was developed as part of another project is available in Bontinck (2018).

3. Results

The total material outflows for the Parkville campus of the University of Melbourne represented 2 280 Mg (t) of materials for 2017. Procurement-related inflows represented 92.8 Mg and non-procurement-related inflows totalled 2 187.2 Mg (to balance material outflows). Procurement-related inflows required 22 587 GJ and 30 891 kL of embodied energy and water, respectively. They were also responsible for 1 477 $GgCO_2e$ of embodied greenhouse gas emissions. These procurement-related material inflows, representing less than 2% of the procurement expenditure data that was obtained, need enough energy to build 8 new average-sized Australian houses (assuming ~3 000 GJ/house based on figures from Stephan and Crawford (2016)) and enough water to fill 12 Olympic swimming pools. They are also responsible for greenhouse gas emissions equivalent to tailpipe emissions from ~9 000 cars driving from Melbourne to Sydney (880 km with an emissions intensity of 180 gCO_2e/vkm).

One of the most important findings of this study is that the proportion of officially recorded procurement-related inflows seems to be responsible for only around 4% of the waste outflows on campus. While this figure was obtained after filtering out a large number of transactions which do not result in a material flow, a certain number of transactions resulting in a material flow were also excluded due to lack of metadata to characterise them. Based on the data available for these transactions, we expect the order of magnitude of the share of procurement-related inflows to remain the same. This has far-reaching implications on the role of the University in promoting circular economy and setting up effective circular economy strategies. This is discussed in detail in Section 4.2.

Fig. 4 depicts the procurement-related material inflows alongside other material inflows and material outflows, to provide an overview of the material flows through the Parkville campus of the University of Melbourne for 2017. Apart from the small contribution of procurement-related material flows, this Sankey diagram reveals the breakdown of material outflows. These are dominated by general waste, representing 66.7% or 1 520.4 Mg of waste, followed by comingled recycling (15%, 342.4 Mg), green waste (3.9%, 90.1 Mg), the recycling of paper and cardboard (3.7%, 83.5 Mg), the recycling of timber (3.5%, 79.1 Mg), the recycling of metals (3.3%, 74.2 Mg) and others. Recycling activities covered in total 28% of the outflows.

[1] https://www.doi.org/10.6084/m9.figshare.7677557

Fig. 5 presents the material flow analysis of the procurement-related inflows and outflows that we studied in depth. Furniture is the single most significant inflow category by mass, representing 43.5% of the total (40.4 Mg), followed by stationary (22.6%, 20.8 Mg), gardening soil (16.2%, 15.05 Mg), food for catering — excluding food sold on campus (5.1%, 4.71 Mg), electronics (3.8%, 3.51 Mg) and energy generation (4.1%, 3.8 Mg). In addition, all packaging (for food and other categories, such as gardening soil) was modelled separately and categorised under ‘Stationary’. Packaging represented 1 Mg in total, with plastic packaging representing 94.6% of the total and the rest disposed of in paper and cardboard bins. These procurement-related inflows were mapped to the following outflows: the University of Melbourne Reuse Centre (UMRC) (48.2%, 44.7 Mg), paper and cardboard (18.8%, 17.4 Mg), gardening soil (16.22%, 15.05 Mg), implying that the soil remains on campus, and others. The UMRC is responsible for collecting furniture and electronics that are being phased out to identify opportunities for re-use (after a potential repair) within the university.

It is important to highlight that the total food outflow was assumed to represent 20% of the total food inflow (food waste), assuming that 80% of that food would be consumed on campus and would exit through sewage pipes.

Of all furniture archetypes, desks represented 57.1% (23 Mg), followed by storage (22.4%, 9 Mg) and chairs (16%, 6.5 Mg). Stationery inflows were dominated by paper (76.2%, 15.3 Mg), followed by filing stationery, such as folders, safes, hole punchers, etc. (13.1%, 2.6 Mg). Food inflows were dominated by milk, which represented 87% of all food procured, or 4 Mg. This was followed by water bottles (3.9%, 182 kg) and coffee (3%, 146 kg). The reported transactions for writing stationery represented 438 kg (2.2% in mass). Electronics were modelled using 57 archetypes, of which the top five by mass were: freezers (21.9%, 888 kg), special lab equipment (16%, 648 kg), electric and electronic cables (13.4%, 545 kg), new personal computer towers (7%, 283 kg) and AA batteries (5.4%, 219 kg). Energy generation is solely represented by the installation of photovoltaic panels, which had a mass of 3.8 Mg and represented 4.4% of the total material inflows in 2017. This level of disaggregation offers detailed information that can support decision-making for circular economy strategies, as discussed in Section 4.1.

While reporting material inflows in mass terms is a useful exercise to identify significant flows and opportunities for circular economy, this is not sufficient to support decision making to improve overall environmental performance. The embodied environmental effects associated with one kg of paper differ greatly from those associated with one kg of electronic materials.

Fig. 6 depicts the embodied energy, water and greenhouse gas emissions associated with the procurement-related material inflows, across the 16 categories of the 189 archetypes used in this study. Note that a logarithmic scale (base 10) had to be used as masses and embodied flows differed by orders of magnitude for different categories. A correlation analysis reveals that embodied energy and greenhouse gas emissions have a small positive correlation with mass as $R^2 = 0.34$ and $R^2 = 0.26$, respectively. Embodied water has a moderate correlation with mass $R^2 = 0.6$. Embodied energy and embodied greenhouse gas emissions are very strongly correlated ($R^2 > 0.99$) because of the greenhouse-gas-emissions-intensive Australian economy. Embodied water is also strongly correlated with both embodied energy and embodied greenhouse gas emissions as $R^2 > 0.9$ and $R^2 = 0.88$, respectively. The weak correlation between mass and embodied environmental flows demonstrates the need to consider additional environmental indicators in material flow analyses, beyond mass. Cost is logically strongly correlated with all embodied environmental flows since it is used directly to calculate them. However, cost was weakly correlated with mass ($R^2 = 0.18$), demonstrating the need to consider both mass and cost simultaneously.

Results show that electronics, while ranking sixth in terms of total inflow mass at 4 Mg, result in the largest embodied environmental

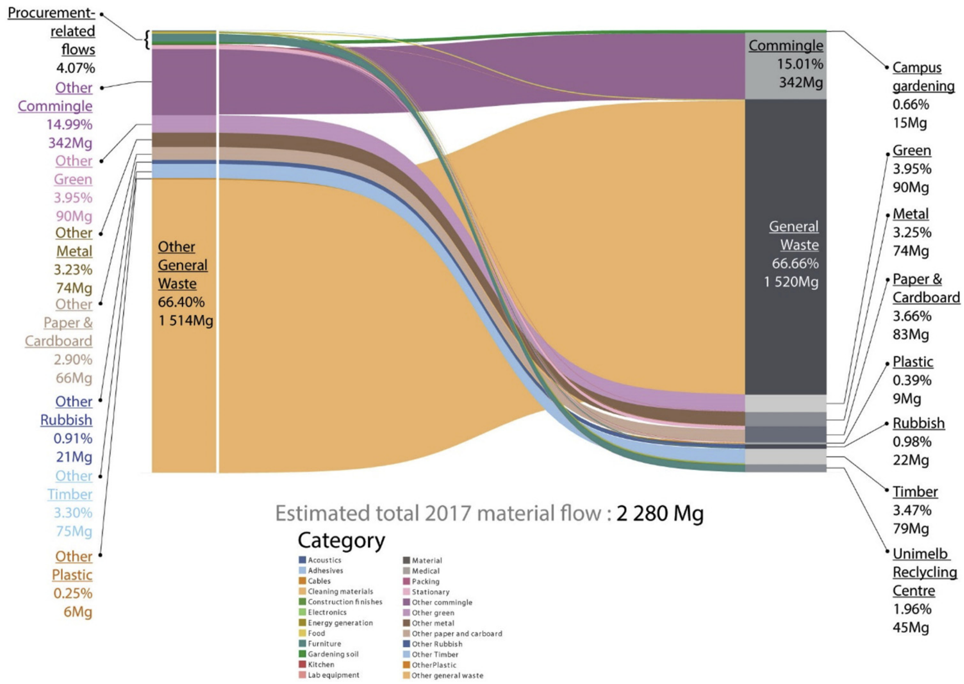

Fig. 4. Material mass flow analysis of the Parkville campus of the University of Melbourne, for 2017, by category.

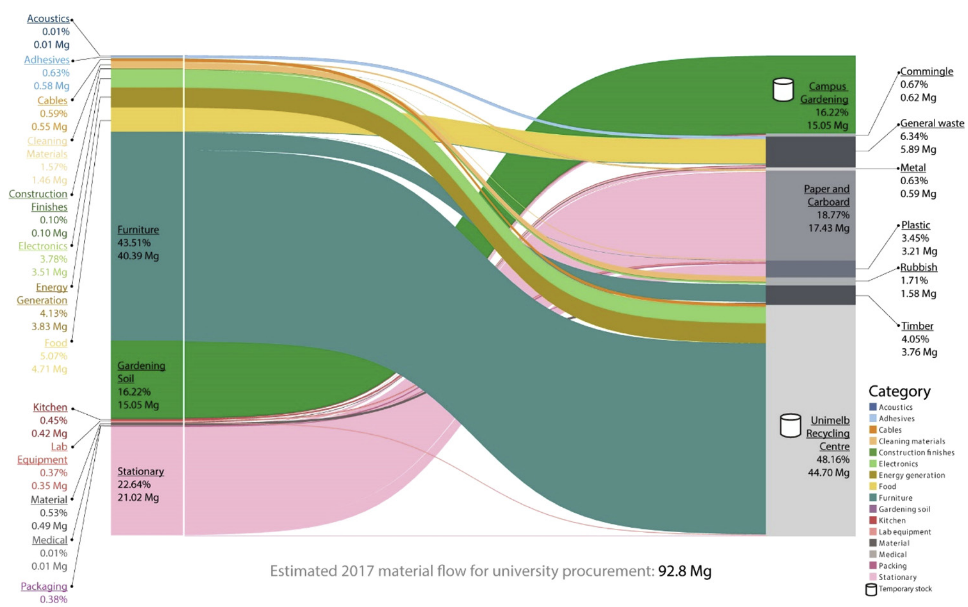

Fig. 5. Procurement-related material mass flow analysis of the Parkville campus of the University of Melbourne, for 2017, by category.

flows, requiring 8 211 GJ of energy (36.4% of the total), 8 445 kL of water (27.3% of the total) and emitting 553 MgCO_2e of greenhouse gases (37.5% of the total), alone. They are also the most expensive, representing 52.5% of the total procurement material inflows, at 1.8 MAUD. Furniture, which weighs the most, requires less resources than electronics to produce and ranks second in terms of embodied energy (4 321 GJ, 19.1%) but third in terms of greenhouse gas emissions (237 MgCO_2e, 16.1%) and embodied water (5 121 kL, 16.6%). It is third in terms of cost, at 13.7% or 471 kAUD. New photovoltaic panels (energy generation) which weigh 3.8 Mg (rank 5), rank second in terms of embodied greenhouse gas emissions (300 MgCO_2e, 18.5%), third in terms of embodied energy (4 175 GJ, 18.5%), and fifth in terms of embodied water (3 771 kL, 12.2%). Photovoltaic panels rank second in terms of cost, at 471 kAUD or 18.5% of the total. Stationary, which ranks second in terms of mass (19.2 Mg), ranks fourth in terms of embodied energy (4 007 GJ, 17.7%), but third in terms of embodied greenhouse gas emissions (239 MgCO_2e, 16.2%) and second only in terms of embodied water (6 407 kL, 20.7%), the latter being driven by the water-intensive production of paper and recycled paper. Stationary ranks fourth in terms of cost, at 335 kAUD (9.7% of the total). Food-related procurement (mainly milk), requires 585 GJ of embodied energy (6th, 2.6%), 4 855 kL of embodied water (3rd due to the water-intensive dairy sector, 15.7%), emits 75 MgCO_2e of greenhouse gases (5th, 5.1%), and costs 67 kAUD (6th, 1.9%). Gardening soil ranks third in terms of weight at 10.4 Mg but has otherwise low energy and greenhouse gas emissions requirements compared to other categories (ranks 13 both). Laboratory equipment, while ranking 13 in terms of mass, are the top 5, 7 and 6 contributor to embodied energy, water and

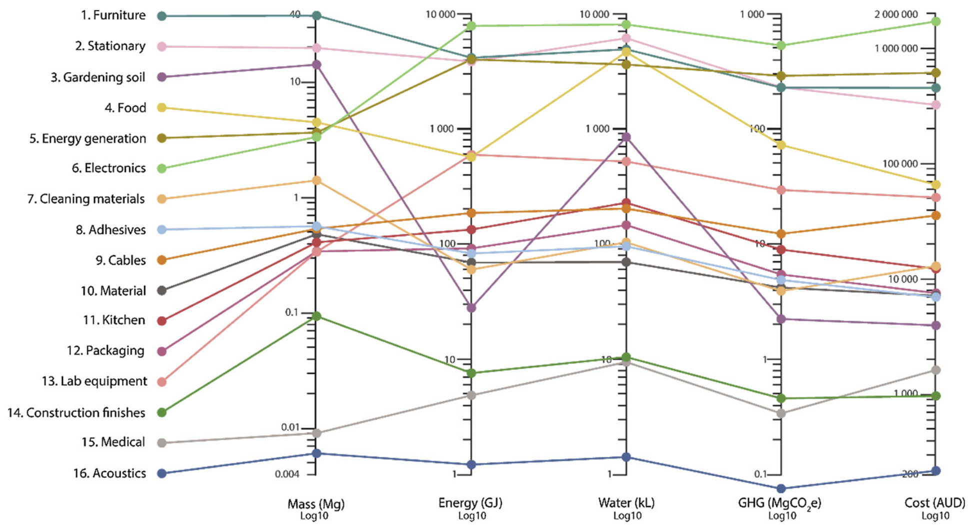

Fig. 6. Mass, embodied energy, embodied water and embodied greenhouse gas emissions (GHG) for procurement-related inflows of the Parkville campus of the University of Melbourne, for the year 2017, by archetype category and using Log10 scales.

greenhouse gas emissions, respectively. These shifts in rankings demonstrate the significant variability in the embodied environmental requirements of different procurement-related inflows and are clearly depicted in Fig. 6.

Fig. 7 depicts the material mass inflows by archetype, using a logarithmic scale, and represents the finest resolution of this study. For each archetype, we indicated the potential of that material inflow for a more circular economy and we categorised that into: re-use (as currently re-used by the university reuse centre), potential recycling (including downcycling and upcycling) and staying on campus (gardening soil). Archetypes are displayed from the heaviest to the lightest. Mass was used to rank these as the quantity of an inflow and its financial value are often the most relevant indicators ('critical mass') that come into play when deciding to implement a circular economy strategy. We only display archetypes that result in a material inflow of more than 100 kg per year (which, combined, represent ~96% of the total procurement-related inflows). We display the mass of the packaging for archetypes of food products.

Results show that particular archetypes yield sufficient inflows to support a more circular economy. Notably furniture archetypes, such as desks (20 093 kg), office chairs (6 449 kg), filing cabinets (5 680 kg) are already being re-used by the furniture reuse centre of the University. Based on data from the centre, 106 148 kg of furniture in 2017, including 16 560 kg of desks, 31 900 kg of chairs and 3 335 kg of filing cabinets were repurposed. The centre also repurposes electronic equipment, such as computers (6 388 kg in 2017) and monitors (5 715 kg in 2017). This might explain the relatively low procurement inflow of PC towers (283 kg) and monitors (173 kg). It is critical to highlight that electronics and information technology represent 12.6% of the total mass of items repurposed by the centre, but that they represent 44.4% of the total financial value of these items. Critical mass is mostly determined by the financial value of goods.

Another important inflow is organic food for plants and landscaping that represented 15 052 kg in 2017, ranked as the second archetype in terms of mass. This demand in gardening material could be covered by composted organic outflows. While the university is already collecting some of its food waste and processing it for compositing on site, the resulting product is too rich to be used directly. Green waste is being sent off-site for composting, but is not being necessarily re-used on campus afterwards. Additional information on the actual fate of green

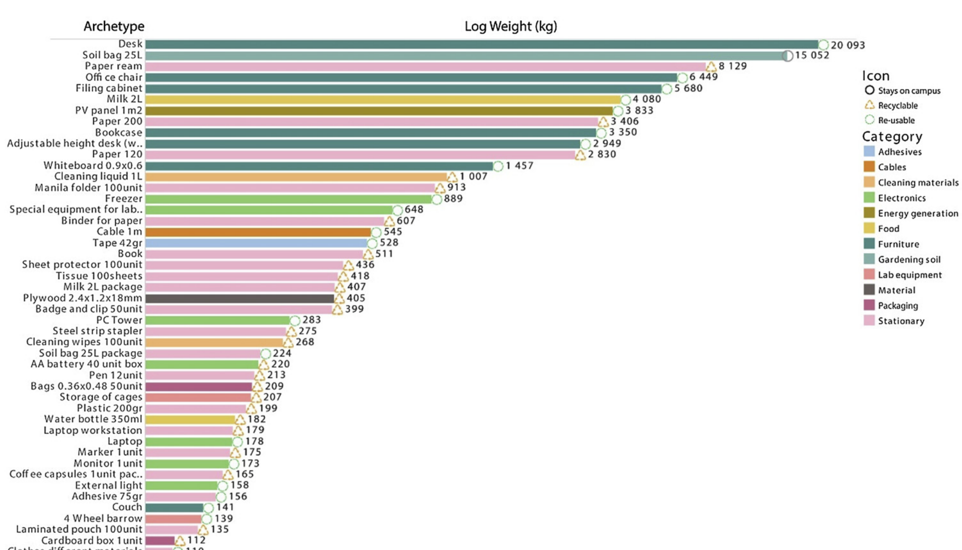

Fig. 7. Procurement material inflows breakdown for the Parkville campus of the University of Melbourne, Australia for 2017, by archetype representing more than 100 kg of mass.

waste would help inform how circular is the gardening soil flow of the University.

3.1. Sensitivity analysis to errors in input-output data

While environmentally-extended input-output data is very well suited to convert financial expenditure to embodied environmental flows, it does suffer from a significant amount of uncertainty which needs to be evaluated. Manfred Lenzen (2000) discusses errors in input-output (and process) life cycle inventories and indicates potential errors at various levels, including in the raw data, in the calculation of the environmental satellites, in the allocation of products to sectors, and others. Lenzen found that the total potential error in input-output life cycle inventories can be up to 85%.

We conduct a sensitivity analysis in order to evaluate the effect of errors in the input-output data on the embodied environmental flows results. To do so, we assumed two different errors ranges, falling within the maximum error identified by Manfred Lenzen (2000), ± 50% (high uncertainty) and ± 70% (very high uncertainty). These uncertainty ranges represent a coarse and aggregated total, accounting for all types of errors identified by Lenzen, and including the fact that we are using 2017 expenditure data, corrected to match 2014–2015 input-output data. Results of the sensitivity analysis are presented in Table 2, by archetype category.

The sensitivity analysis demonstrates the high level of uncertainty associated with environmental-extended input-output analysis. The embodied environmental flows results should therefore be considered as orders of magnitude rather than precise measurements. Considering a medium level of uncertainty, the orders of magnitude of embodied energy and water are not affected by uncertainty. However, greenhouse gas emissions could potentially be one order of magnitude lower than what is calculated, should there be a 50% overestimation of the results.

4. Discussion

This study contributes to the existing body of knowledge on material and embodied environmental flow analysis of university campuses in terms of method, scope and findings.

The method adopted in this study can provide an efficient and flexible manner to quantify procurement-related material inflows for universities and large organisations. The use of archetypes enables the researcher to provide a high resolution where needed (e.g. 57 archetypes for electronics) and a lower resolution for flows which are less significant from a mass, financial and/or environmental perspective (e.g. 3 archetypes for adhesives). It also facilitates further research by extending the indicators attached to each archetype. For instance, additional embodied flows can be added to each archetype, recycled fractions, and other useful information to broaden the study.

Our findings reveal that procurement inflows on university campus are only responsible for a small fraction (around 4% (based on our calculations) and up to 5–7% (based on our estimations) in the case of the University of Melbourne) of waste outflows collected on campus. This can be explained by at least two factors. Firstly, the nature of universities as large institutions that host a high number of staff and students on campus, which are in turn responsible for significant material inflows and outflows that are not related to university

Table 2
Sensitivity analysis of embodied energy, water and greenhouse gas emissions results to different levels of uncertainty in input-output data, by archetype category.

Category	**Energy (GJ)**	Energy ± 50% (high uncertainty) (GJ)	Energy ± 70% (very high uncertainty) (GJ)	**Water (kL)**	Water ± 50% (high uncertainty) (kL)	Water ± 70% (very high uncertainty) (kL)	**GHG ($MgCO_2$-e)**	GHGE ± 50% (high uncertainty) ($MgCO_2e$)	GHGE ± 70% (very high uncertainty) ($MgCO_2e$)
Acoustics	**1.2**	0.6 – 1.8	0.4 – 2	**1.4**	0.7 – 2.1	0.4 – 2.4	**0.07**	0.04 – 0.11	0.02 – 0.13
Adhesives	**83.9**	41.9 – 125.8	25.2 – 142.6	**96.9**	48.4 – 145.3	29.1 – 164.7	**4.9**	2.5 – 7.4	1.5 – 8.4
Cables	**189.5**	94.8 – 284.3	56.9 – 322.2	**207.1**	103.5 – 310.6	62.1 – 352	**12.5**	6.2 – 18.7	3.7 – 21.2
Cleaning materials	**60.7**	30.3 – 91	18.2 – 103.1	**105.1**	52.6 – 157.7	31.5 – 178.7	**3.9**	2 – 5.9	1.2 – 6.7
Construction finishes	**7.5**	3.8 – 11.3	2.3 – 12.8	**10.4**	5.2 – 15.6	3.1 – 17.7	**0.5**	0.2 – 0.7	0.1 – 0.8
Electronics	**8,211.5**	4,105.7 – 12,317.2	2,463.4 – 13,959.5	**8,444.5**	4,222.3 – 12,666.8	2,533.4 – 14,355.7	**553.1**	276.6 – 829.7	165.9 – 940.3
Energy generation	**4,174.6**	2,087.3 – 6,261.9	1,252.4 – 7,096.8	**3,771.2**	1,885.6 – 5,656.8	1,131.4 – 6,411	**300.0**	150 – 449.9	90 – 509.9
Food	**584.8**	292.4 – 877.2	175.4 – 994.1	**4,854.6**	2,427.3 – 7,281.9	1,456.4 – 8,252.8	**74.6**	37.3 – 112	22.4 – 126.9
Furniture	**4,320.8**	2,160.4 – 6,481.2	1,296.2 – 7,345.3	**5,120.8**	2,560.4 – 7,681.2	1,536.2 – 8,705.3	**237.1**	118.5 – 355.6	71.1 – 403
Gardening soil	**28.0**	14 – 42.1	8.4 – 47.7	**875.0**	437.5 – 1,312.6	262.5 – 1 487.6	**2.2**	1.1 – 3.4	0.7 – 3.8
Kitchen	**135.9**	67.9 – 203.8	40.8 – 231	**233.1**	116.5 – 349.6	69.9 – 396.2	**9.1**	4.5 – 13.6	2.7 – 15.4
Lab equipment	**613.7**	306.9 – 920.6	184.1 – 1,043.3	**535.0**	267.5 – 802.5	160.5 – 909.5	**30.2**	15.1 – 45.2	9 – 51.3
Material	**69.9**	35 – 104.9	21 – 118.8	**70.6**	35.3 – 105.9	21.2 – 120	**4.2**	2.1 – 6.3	1.3 – 7.2
Medical	**4.8**	2.4 – 7.2	1.4 – 8.2	**9.4**	4.7 – 14.1	2.8 – 16	**0.3**	0.2 – 0.5	0.1 – 0.6
Packing	**93.0**	46.5 – 139.5	27.9 – 158.1	**148.8**	74.4 – 223.1	44.6 – 252.9	**5.5**	2.8 – 8.3	1.7 – 9.4
Stationary	**4,006.9**	2,003.4 – 6,010.3	1,202.1 – 6,811.7	**6,406.8**	3,203.4 – 9,610.1	1,922 – 10,891.5	**238.7**	119.4 – 358.1	71.6 – 405.8
Total	**22,587**	**11,293 –33,880**	**6,776 – 38,397**	**30,891**	**15,445 – 46,336**	**9,267 – 52,514**	**1,477**	**739 – 2,215**	**443 – 2,511**

Note: GHGE = greenhouse gas emissions; Commas are used as thousands separators in this table for formatting purposes (spaces are used throughout the paper).

procurement. Secondly, food and beverage retail is known to have waste generation rates per unit area, up to thirty times that of offices and classrooms (City of Melbourne, 2017). The material inflows associated with food and beverages tenants on campus are not included in the procurement data of the university. This has significant implications in terms of designing circular economy strategies for universities.

Another insight is the lack of strong correlation between the mass of inflows and their associated embodied environmental flows as well as the weak correlation between mass and cost. While most existing studies on material flow analysis focus on the mass of materials, we demonstrate the need to broaden the scope of such studies and include embodied environmental flows as well as cost, in order to determine critical inflows on which to focus. For example, electronics have an average cost of 452 kAUD/Mg (38.6 times higher than furniture) and result in embodied flows of 2 052 GJ/Mg (19 times higher than furniture), 138 $MgCO_2e$/Mg (23 times higher than furniture) and 2 110 kL/Mg (17 times higher than furniture) for energy, greenhouse gas emissions and water, respectively. The differences in orders of magnitude between the financial and environmental intensities of archetypes demonstrate how critical it is to consider both their financial and environmental performance, beyond using mass as the single indicator of the analysis.

4.1. Towards a more circular economy for university campuses and other large organisations

Based on the research process and the findings of this study, we propose several recommendations to help transition material flows on university campuses (and more broadly in large organisations) towards a more circular economy. The most significant are discussed below.

Firstly, universities and large organisations would largely benefit from collecting relevant and disaggregated inflows and outflows data. During this study, the processing, filtering and cleaning of the procurement data represented the single most significant task, requiring the most time. Since waste data was regularly collected at a relevant level of disaggregation, it was much easier to understand where materials where exiting the campus and in what form, compared to tracing their origin. We strongly recommend collecting consistent procurement data for universities and large organisations alike, where transactions are allocated to correct accounts, contain descriptive invoices of the exact item purchased and where possible include a link to the supplier. Universities and large organisations being significant clients in terms of volume and financial expenditures can require suppliers to provide additional relevant metadata that can simplify material flow analyses, such as the weight of a product, and its volume. Ideally, each product would include a material breakdown by mass that is calculated according to a national or international standard, much like the environmental product declarations (International Standard 14025/TR, 2006). This would significantly facilitate studies such as this one and help universities and large organisations better understand the material footprint of their procurement. In addition to procurement data, universities and large organisations can organise audits on material inflows stemming from tenants on campus, such as those conducted at the University of Melbourne by Liang et al. (2018) to quantify the Nitrogen footprint of the University. By requiring tenants to report on their purchases of materials (notably disposable items) as well as sales of such materials (e.g. disposable coffee cups), universities will be able to understand where materials are coming from, and to better manage these inflows.

Once reliable data are obtained and a material (and embodied environmental) flow analysis is conducted, procurement-specific measures can be taken to transition to a more circular economy. Transitioning to services rather than purchasing their own products is a proven circular economy strategy (Tukker, 2015), as it shifts the responsibility to the provider, which in turn benefits from using durable, efficient, and recyclable and re-usable products and components. The service provider has a product stewardship at the end of the service of the product. In this sense, the University of Melbourne is already using such services, such as the Philipps pay-per-lux scheme[2] for its lighting. Another important strategy is to setup local re-use centres, such as the University of Melbourne Reuse Centre (UMRC). With the significant volume and mass flows of valuable materials within a university (or large organisation), there is significant scope for local circularity. This re-use of materials can save significant amounts of money compared to buying new products. In 2017 alone, the UMRC saved an estimated 3 Million AUD of electronics and furniture. Using the same environmentally extended input-output analysis approach described in Section 2.4, we estimate that this re-use also saved 23 673 GJ of embodied energy, 24 821 kL of embodied water and avoided the emission of 1 466 $MgCO_2e$. These figures are similar to those associated with embodied flows related to the procurement material flow of the Parkville campus in the same year, demonstrating the significance of repurposing existing furniture and electronic equipment, instead of purchasing anew. Another strategy consists of sharing expensive and embodied energy intensive equipment in-house. For example, the Melbourne School of Design has created a central sharing hub (the ABP loans portal) for advanced electronic equipment (e.g. virtual reality stations, projector kits, etc.) that staff can borrow. This reduces the total number of items that need to purchased and ensures that items in service are well maintained. Looking only at projectors and assuming a 30% reduction in the number of projectors purchased, the sharing program saves 8.8 GJ, 570 $kgCO_2e$ and 9 654 L of embodied energy, greenhouse gas emissions and water over a 3 years period (assumed lifespan of shared projectors), respectively. Overall, electronics and E-waste are significant flows that need to be taken into consideration in comprehensive strategies, notably within higher education institutions (Agamuthu et al., 2015). Strategies pertaining to applying circular economy strategies to procurement-related material flows are directly applicable to large organisations that operate like universities, e.g. offices and banks, as they host similar activities, such as desk-based work with a computer and monitor, printing and filing.

Lastly, but most importantly, the largest opportunities to transition to a more circular economy on campus lies in non-procurement material flows, eliminating large quantities of waste, while educating future generation to use materials more consciously. Indeed, this study demonstrated that an estimated 96% of all waste outflows on campus (2 187.2 Mg) originated outside procurement-related activities. Based on the bins audits from the waste data, these waste streams were predominantly food scraps and paper cups. As such, if the university can effectively influence tenants using some combination of information, incentives and/or enforceable lease requirements, there is an opportunity to reduce such waste on campus. Over recent years the University has taken action to reduce food waste and packaging, for example by co-ordinating the purchase of discounted branded reusable coffee cups[3] and setting up a plate washing service at the main student food retail building (started in 2019), where the majority of food and beverage retail is located on campus. To date, there is not enough data gathered to be able to quantify the material flows associated with these initiatives. It is noted that these current initiatives both have limitations, with personal coffee cups requiring people to carry them around, and the plate washing service applying to those who eat-in at the main student food retail building only. The University is currently investigating how initiatives like these can be enhanced and complemented, for example by offering a period of free rent for the tenant with the highest environmental performance on campus, each year. It is noted that other approaches are available, for example branded reusable cups and containers can be sold at any hospitality tenant shop on

[2] http://www.ellenmacarthurfoundation.org/case-studies/selling-light-as-a-service

[3] https://sustainablecampus.unimelb.edu.au/a-z/k/keep-cups

campus and can be returned to university-operated kiosks for washing or recycling, at their end of life. To have the greatest uptake, such re-useable cups and containers should not be prohibitively expensive so that students or staff that might not have a re-usable cup/container at the time of purchase can easily purchase a re-usable container on the spot, and later return their extra-container to a kiosk for a partial refund. The Swap-Cup[4] initiative, which enables coffee drinkers to use a washed re-usable cup and get a token for a dirty cup (that they can swap for a clean cup the following time), is a step in the right direction. However, this is a grassroots movement that is not generalised. In comparison, university-affiliated student bodies have already implemented similar schemes, e.g. re-usable cups for student circles at the Université Libre de Bruxelles, Belgium.[5]

Anecdotally, University staff know that not all food waste and packaging come from on-campus tenants. With deliveries, such as Uber-eats, becoming increasingly popular, (particularly for staff and students who are on campus after the on-campus cafes have closed) the challenge in terms of waste management remains.

The measures suggested above can contribute to reduce material extraction, product manufacturing, associated embodied environmental flows and effects, and transition to a more circular economy where waste is reduced and eliminated, outflows are re-used and are ultimately recycled. On university campuses, these measures not only improve the environmental performance of the university, but they also help educate future generations of humans in using less materials. A successful engagement with relevant stakeholders would be needed to gather additional behavioural and social data that can help enact more robust circular economy plans, as outlined by Mendoza et al. (2019).

4.2. Limitations and future research

This study relies on a set of different models to represent reality, and thus, like any research endeavour, suffers from certain limitations. Firstly, the underlying procurement data had to be manually filtered, cleaned and adjusted to be able to extract material inflow from financial transactions. For the quality of results to be ensured, it is critical for this paper and future studies to have improved data on material flows. Investing in better data systems would provide many possibilities to better understand the whole procurement system, not only in this area of research but in others too.

Secondly, and as mentioned in Section 1.1, the construction activity has been omitted to maintain a manageable scope. We believe that should construction activities be included, they would by far outweigh non-construction related material flows in terms of mass, even when normalised on an annual basis. Yet, this remains to be validated in future research. Furthermore, hazardous waste outflows were not covered in the scope of this work, although they could have significant adverse environmental effects and would warrant further study. Another area of future research is a focused study on food inflows, food waste and food packaging in particular. This could be an extension of the work already conducted by Liang et al. (2018) on the nitrogen footprint of The University of Melbourne.

Thirdly, the environmentally extended input-output analysis that we conducted provides an overall estimate of embodied environmental flows. A more detailed hybrid analysis would yield more reliable results by integrating more accurate and product-specific process data where available (Crawford et al., 2018; Pomponi and Lenzen, 2018).

Fourthly, the service life of archetypes should be factored in to better model how long the remain in the in-use stock. Fifthly, we assumed that 20% of the food was wasted. It would be more accurate to understand the actual rate of food waste in order to better manage that on campus. Sixthly, for procurement-related outflows we assumed that inflows are always correctly disposed in the correct bins while the audit of March 2017 found that 11.22% of plastics and 6.59% paper and cardboard were disposed of in the land-fill bin. Finally, the use of archetypes, while facilitating the analysis and streamlining it, introduces uncertainties. It was almost impossible to gather enough data about the material breakdown of a particular archetype. This is due to the lack of (publically) available information, manufacturing secrecy, lack of information from the manufacturer[6] and other barriers that hinder a transparent and reliable use of information. When the detailed material breakdown could be collected, it was typically for simple archetypes made of a single material or two. Furthermore, we had to rely on third-party data to estimate the mass of a particular archetype, when no specific data was available from the supplier. This archetypal approach would gain in reliability and usefulness if additional data on the material breakdown of particular products were to be made available.

5. Conclusion

This paper has proposed a granular and data-intensive approach to quantifying the material flows of a university campus and associated embodied environmental flows. This exercise has demonstrated that procurement-related material inflows represent a small fraction of the total inflow of materials on campus. This means that universities need to engage with a broad range of stakeholders to reduce their material flows, and notably to cut down food and beverage waste from food retailed on campus and off campus. Results also demonstrate the need to move away from solely conducting a material flow analysis focusing on mass but to also include embodied environmental flows and cost as these were found not to be correlated with mass. Different materials, with different densities, can have varying environmental effects and cost. The proposed circular economy strategies associated with procurement-related inflows are also relevant for large organisations, beyond universities and higher education institution. By following these strategies, the University of Melbourne and others will be able to reduce their direct and indirect environmental effects and help mitigate the looming climate catastrophe and resource depletion.

Authors contributions

AS, GH and JA designed the original research idea and secured the funding. AS, SM, GH and JA collected the data. AS and SM developed the modelling approach, conducted the analysis and modelled the material flows and associated embodied environmental flows. AS designed the figures. SM made the figures and AS edited them. AS, SM, GH and JA wrote the paper. SM and AS formatted the datasets for sharing. AS revised the paper in light of the comments of reviewers.

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[4] www.swapcup.org

[5] www2.ulb.ac.be/environnement/SGO.html

[6] In one instance, we asked a manufacturer directly about the weight of the bottles used for cleaning products. The response was that the manufacturer does not have access to this information.

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