Level 3 Industrial Case Study

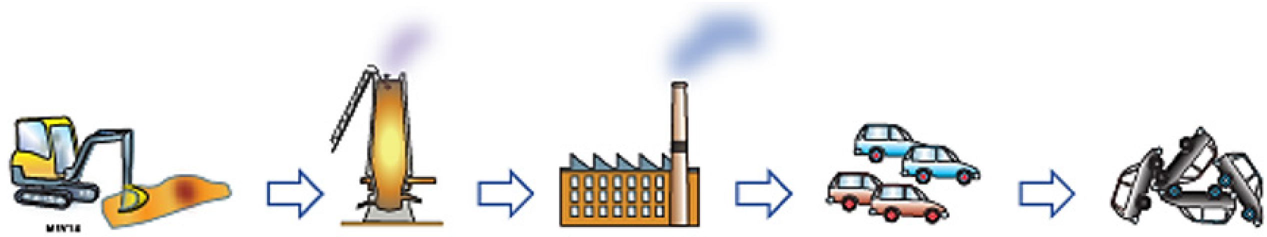
Circular Economy Data and Tools for Materials Teaching

Claes Fredriksson and Mauricio Dwek

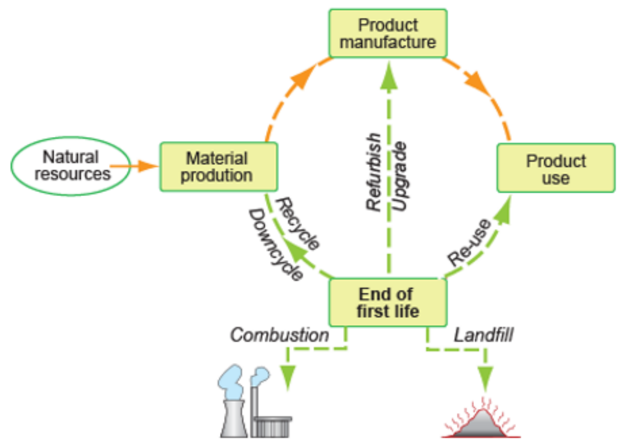
Ansys Education Team

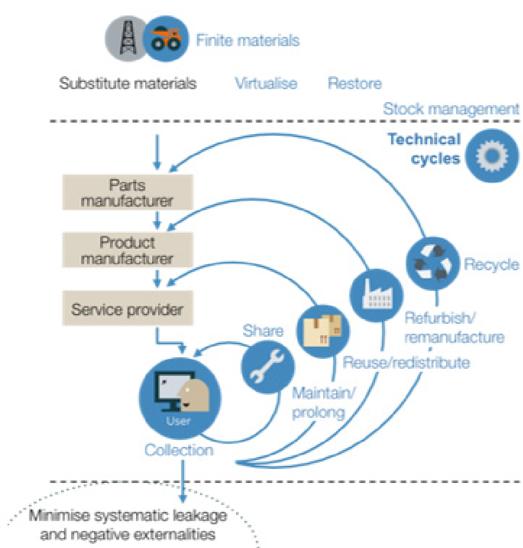
The components of circular economy

The unsustainable nature of linear production models has led to the emergence of new, circular industrial systems. The problems of the traditional and now obsolete handling of products, in terms of material flow, occur both at the extraction and production of materials as well as at the end of product life. Limited natural resources, energy use and pollution are issues with virgin material production whereas toxic waste, lost economic value and landfill space are some of the negative consequences if products are discarded carelessly.



Life-cycle thinking is fundamental to modern product design and must be the starting point when trying to improve environmental credentials. Our version is shown in this model, developed for Eco Audits by Prof Mike Ashby. It shows the four phases of a first product life with 5 end-of-life scenarios. Landfill represents the linear material flow, combustion represents energy recovery, which is possible for polymers and some composites, but where the material value is lost. Downcycling, recycling and various form of repair or remanufacturing all reduce the need for new material whereas re-use of intact (second-hand) products also eliminates the manufacturing phase.





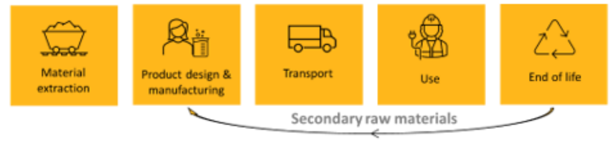
SOURCE: Adopted from original by the Ellen MacArthur Foundation

Circular economy is an incentive to increase resource efficiency, where materials flow in a closed loop (cradle-to-cradle instead of cradle-to-grave). Future engineers will be a key part of this transition. In a circular model, materials remain a valued asset to be conserved for reuse, minimizing waste. It also implies the use of renewable energy, material tracking (quality and location), and designing products that aid with material restoration and reuse.

In a product-centric approach, reuse and re-manufacturing strategies are relatively straight¬forward but there are still issues when attempting to close material loops via recycling scenarios. Even now, secondary raw materials are scantly used due to difficulties in finding suitable applications or a lack of confidence in their properties and performance. This case study is inspired by Ashton et al. (2018), who used Ashby property charts to identify applications for recycled polymeric multi-materials from toothbrushes.

What's the problem?

As we start closing material or product loops by adopting circular strategies, new questions arise concerning stakeholders.

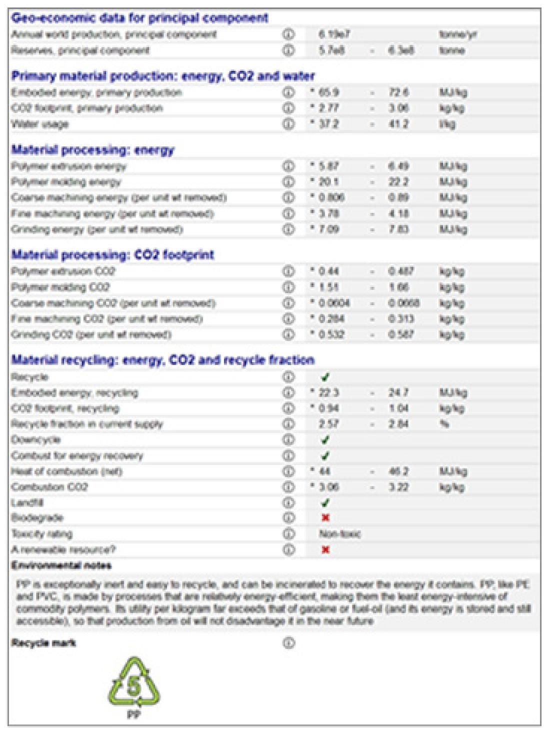


If we consider the recycling of products for instance, recyclers will generate secondary raw materials, which will in turn be available to product designers and manufacturers. However, not all recycled materials retain the properties of the virgin materials from which they originate. This is due to several factors. For example, contaminants introduced somewhere along the way, or processing limitations. It is especially true for sophisticated alloys, polymer materials and composites in general. To bridge this gap between end-of-life and product design stakeholders, Granta EduPack and Selector's databases of material properties can be explored. We can use our visualization and comparison tools to identify applications for secondary raw materials. There are also new opportunities to use a systematic and generalized method to determine applications for secondary raw materials. It is based on the identification of virgin materials that can be potentially replaced.

What can Granta EduPack do?

The databases of EduPack can, of course, act as a source of information and facts, useful for circularity in both design and production. Geo-economic data allows discussions about availability and supply chain. There is energy and CO_2 data for material production, processing, and recycling (also used in Eco Audit). Renewable resource information as well as end-of-life data and options are available.

By using data on the embodied energy of virgin materials and the available data for energy required when recycling the same material, it is possible to estimate potential gains, at least for the second life of a component. You can also explore various fractions of recycled material in the feedstock. In addition, it is possible to assess the associated reduction in carbon footprint, using the emission data on virgin and recycled materials, respectively. Heat of combustion data makes it possible to compare scenarios in terms of energy recovery for incinerated organic material, like thermosets or some composites.



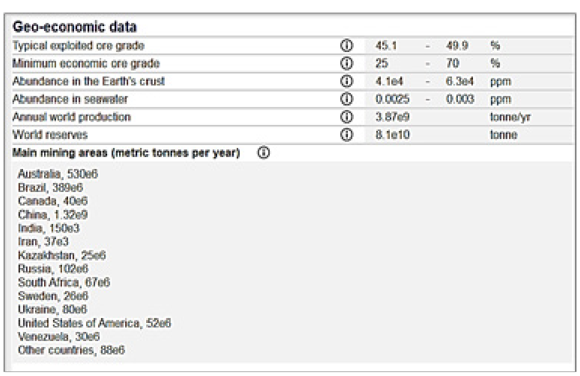
Geo-economic data for principal component		
Annual world production, principal component	6.19e7	tonne/yr
Reserves, principal component	5.7e8 - 6.3e8	tonne
Primary material production: energy, CO_2 and water		
Embodied energy, primary production	* 65.9 - 72.6	MJ/kg
CO_2 footprint, primary production	* 2.77 - 3.06	kg/kg
Water usage	* 37.2 - 41.2	l/kg
Material processing: energy		
Polymer extrusion energy	* 5.87 - 6.49	MJ/kg
Polymer molding energy	* 20.1 - 22.2	MJ/kg
Coarse machining energy (per unit wt removed)	* 0.806 - 0.89	MJ/kg
Fine machining energy (per unit wt removed)	* 3.78 - 4.18	MJ/kg
Grinding energy (per unit wt removed)	* 7.09 - 7.83	MJ/kg
Material processing: CO_2 footprint		
Polymer extrusion CO_2	* 0.44 - 0.487	kg/kg
Polymer molding CO_2	* 1.51 - 1.66	kg/kg
Coarse machining CO_2 (per unit wt removed)	* 0.0604 - 0.0668	kg/kg
Fine machining CO_2 (per unit wt removed)	* 0.284 - 0.313	kg/kg
Grinding CO_2 (per unit wt removed)	* 0.532 - 0.587	kg/kg
Material recycling: energy, CO_2 and recycle fraction		
Recycle	✓	
Embodied energy, recycling	* 22.3 - 24.7	MJ/kg
CO_2 footprint, recycling	* 0.94 - 1.04	kg/kg
Recycle fraction in current supply	2.57 - 2.84	%
Downcycle	✓	
Combust for energy recovery	✓	
Heat of combustion (net)	* 44 - 46.2	MJ/kg
Combustion CO_2	* 3.06 - 3.22	kg/kg
Landfill	✓	
Biodegrade	✗	
Toxicity rating	Non-toxic	
A renewable resource?	✗	

Environmental notes

PP is exceptionally inert and easy to recycle, and can be incinerated to recover the energy it contains. PP, like PE and PVC, is made by processes that are relatively energy-efficient, making them the least energy-intensive of commodity polymers. Its utility per kilogram far exceeds that of gasoline or fuel-oil (and its energy is stored and still accessible), so that production from oil will not disadvantage it in the near future.

Recycle mark

PP



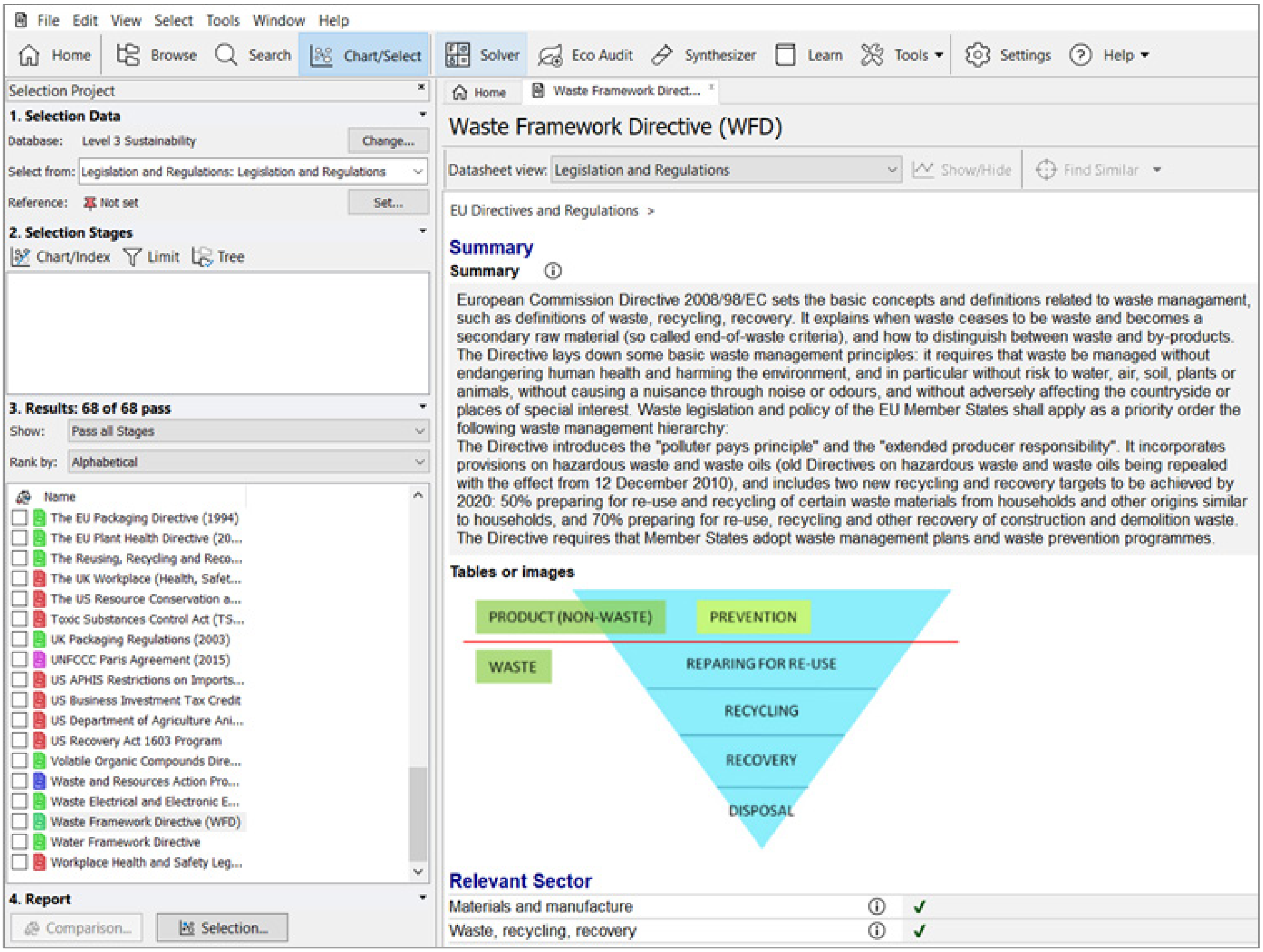
Geo-economic data		
Typical exploited ore grade	45.1 - 49.9	%
Minimum economic ore grade	25 - 70	%
Abundance in the Earth's crust	4.1e4 - 6.3e4	ppm
Abundance in seawater	0.0025 - 0.003	ppm
Annual world production	3.87e9	tonne/yr
World reserves	8.1e10	tonne

Main mining areas (metric tonnes per year)

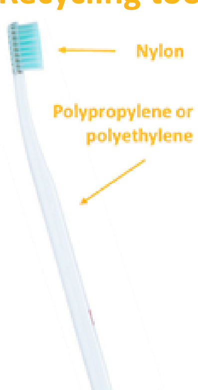
Australia, 530e6
Brazil, 389e6
Canada, 40e6
China, 1.32e9
India, 150e3
Iran, 37e3
Kazakhstan, 25e6
Russia, 102e6
South Africa, 67e6
Sweden, 26e6
Ukraine, 80e6
United States of America, 52e6
Venezuela, 30e6
Other countries, 88e6

The geo-economic data also includes resource information, such as Abundance and World reserves which gives an indication of the urgency for closing the loop of specific materials. The main mining areas and criticality information can support risk assessments of a product supply chain and potential benefits for recycling. There is even data on typical and economic ore grades to add depth to the assessment of feasibility when it comes to circular materials flow.

In addition to numerical data, the datasheets contain written information about composition, tradenames, recyclability, and typical uses of each material, which is searchable by keywords within the database. To emphasize the wide range of circularity-related assets embedded in the software, we display a screenshot from the Legislation and Regulation subset of the sustainability database. It summarizes important legal frameworks relating to materials. For example, the EU recycling directive or US resource conservation act.

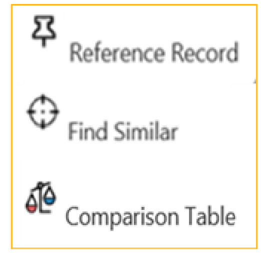


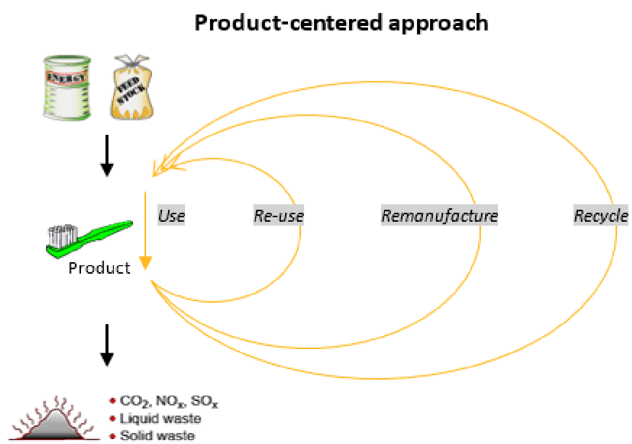
Recycling toothbrushes...



In this case study we are going to look at the example of recycling toothbrushes. The thought of trying to re-use toothbrushes may put you off but there are nevertheless benefits to trying to recover the material from discarded ones, based on the large numbers replaced every year. Toothbrushes are usually made of two (and sometimes more) polymers. They can be recycled after use (after being shredded) via a new injection process, adding linear low-density polyethylene (30% in weight) becoming a multi-material of unknown properties. This new recycled material has to be tested and characterized to serve as a secondary raw material, in order to find the best use for it.

The secondary raw material data can be manually added to the MaterialUniverse for comparison in the database. This allows us to identify potential applications to close the material loop at the end of life of the product. This approach was originally developed in a 2018 paper written by Ashton et al. in a collaboration between the Federal Universities of Rio Grande do Sul and Espírito Santo in Brazil and the Grenoble Institute of Technology in France. A new set of tools in Granta EduPack has now made it possible to expand this idea.



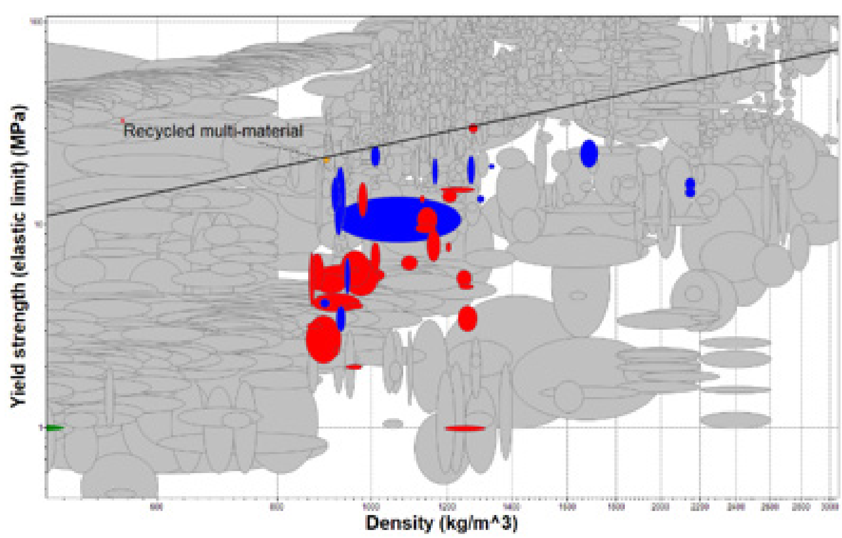


Our model (Fredriksson et al.) of circularity follows a product-centered approach aligned with the principles of an Eco Audit, instead of a full LCA. In this model, the product (toothbrush) is at the center, rather than the user, and the resources going into the product are limited to just the feedstock and energy. The waste is simplified to only encompass CO_2 emissions, since this is directly related to the energy use and also constitutes the main concern in global warming and climate change as well as in related regulations.

Secondary raw material from recycled toothbrushes

Ashton et al. identified applications for a recycled polymeric multi-material obtained from comminuting and co-injecting toothbrushes. Their method used material property charts to gather potential areas of application based on materials with equal or inferior mechanical performance. It consisted in comparing the secondary material attributes acquired by characterization tests (density, yield strength, ultimate strength, elongation at break, Young's modulus and tan delta) with thousands of materials datasheets found in the Granta Selector software.

Their recycled material was compared using Ashby charts and applying filters based on potential applications and mechanical performance indices. Materials with higher performance were eliminated and applications were selected based on an analysis of three remaining candidate materials for substitution. The results showed that PE-LD, PVC and leather could be substituted by the secondary raw material and a subsequent analysis indicated cable coverings, containers/bowls and shoe components as potential applications.

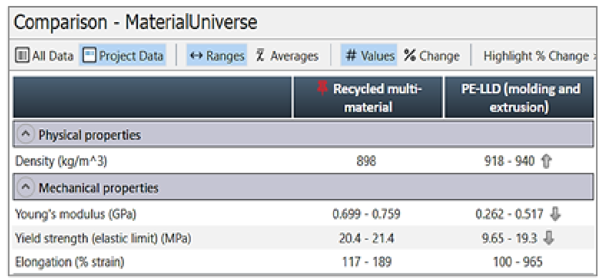


Identifying applications using comparison table and find similar tool

Secondary Raw Material (from test data)	Recycled multi-material [5]	PE-LLD (molding and extrusion) [6]
Density (kg/m³)	898	918 - 940
Young's modulus (GPa)	0.699 - 0.759	0.262 - 0.517
Yield strength (MPa)	20.4 - 21.4	9.65 - 19.3
Elongation (% strain)	117 - 189	100 - 965

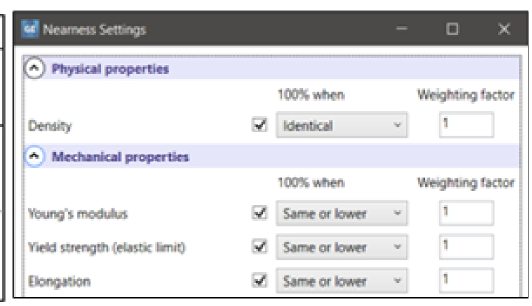
In the extended method, the data for the secondary raw material is also added using the Add record feature in the contextual Tools menu. Data from the original study is shown here. We include a comparison with the virgin polymer material, PE-LLD, added to aid in the extrusion process. The recycled multi-material is less dense, stiffer and stronger than pure PE-LLD.

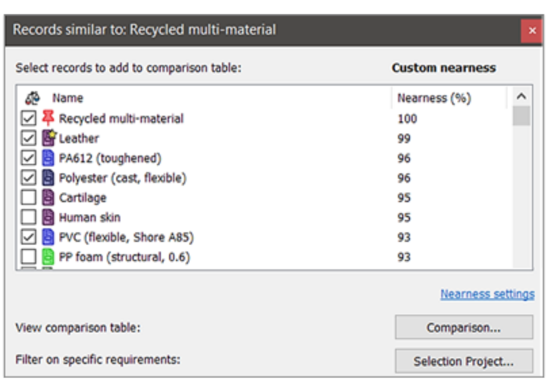
Set Reference lets the user mark a material to benchmark against, in this case it will be the secondary raw material. This record will be identified by a red pin which makes it easy to find. The Comparison Table feature lets you compare candidates side-by-side to facilitate an overview of multiple material properties (more than two). There are both menu options to reach these features and possibilities to right-click.



The next step is to use the Find similar feature. This tool was originally developed to quickly find replacement materials for substitution. The reference record can now be used to find the material in the database that is most similar to it, or with properties inferior to a reference material. Higher, lower and identical values are possible, and the properties can be chosen freely and be given weighting factors for maximum versatility.

Criteria Type	Description
Identical	Only having the same data value as a reference record is considered as no difference. Values higher or lower than the reference record are considered as percentage differences.
Same or higher	Having the same data value or a higher data value than the reference record is considered as no difference. Values lower than the reference record are considered as percentage differences.
Same or lower	Having the same data value or a lower data value than the reference record is considered as no difference. Values higher than the reference record are considered as percentage differences.





In our case, it is assumed that the secondary raw material will substitute a material with similar density but the same or lower values for the mechanical properties; stiffness, strength and elongation. The result is a list of materials, ranked by the nearness to the reference material in terms of the selected properties. This approach shows that leather, nylon and polyester are similar but slightly inferior to the multi-material, hence suitable candidates for replacements. Human tissue is discarded here but PVC might also be a candidate with 93% nearness.

The properties of the recycled multi-material from the original study are now compared to three top candidates.

Comparison - MaterialUniverse

All Data | Project Data | ↔ Ranges | x̄ Averages | # Values | % Change | Highlight % Change > 10 | Apply

	Recycled multi-material	Leather	PA612 (toughened)	PVC (flexible, Shore A85)
Composition overview				
Form	Bulk material	Other	Bulk material	Bulk material
Material family		Natural	Plastic (thermoplastic, semi-crystalline)	Plastic (thermoplastic, amorphous)
Physical properties				
Density (kg/m^3)	898	810 - 1050	1000 - 1020 ↑	1330 - 1340 ↑
Mechanical properties				
Young's modulus (GPa)	0.699 - 0.759	0.1 - 0.5 ↓	0.49 - 0.611 ↓	0.03 - 0.035 ↓
Yield strength (elastic limit) (MPa)	20.4 - 21.4	2 - 5 ↓	19.6 - 24.4	19 - 20 ↓
Elongation (% strain)	117 - 189	18 - 75 ↓	55.4 - 79.7 ↓	90 - 100 ↓

The candidate materials found for substitution were the same as in the initial study (after excluding biological materials such as cartilage, as well as thermoset polyesters, which do not comply with the processing route envisioned in this case). Using the price data available for comparison of materials in the software, the differences become evident, as shown in the figure below. This confirms that a high added value application would be in the shoe industry, as proposed by the authors.

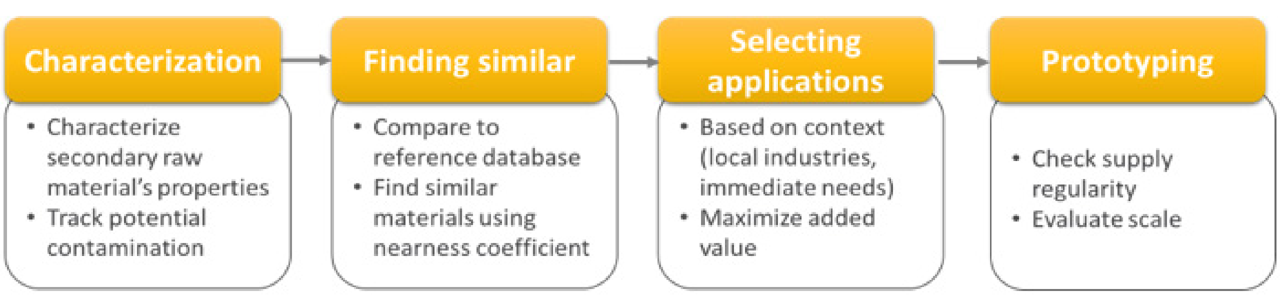
Comparison - MaterialUniverse

All Data | Project Data | ↔ Ranges | x̄ Averages | # Values | % Change | Highlight % Change > 10 | Apply

	Recycled multi-material	Leather	PA612 (toughened)	PVC (flexible, Shore A85)
Price				
Price (USD/kg)		16.6 - 20.7	10 - 10.1	2.55 - 2.58
Price per unit volume (USD/m^3)		13400 - 21700	10000 - 10300	3390 - 3460

Reality check

A general method for finding secondary raw materials applications is proposed, in which the materials are characterized and Granta EduPack is used to find similar materials that provide insights for potential applications with the highest possible added value. If one of these applications were to be seriously considered in an industrial setting, an additional prototyping step to evaluate the scale and to check supply regularity in terms of volume and composition should be added, as shown in the figure below.



This revised method using Granta EduPack's advanced tools yielded similar results to the original study, with the added benefit of focusing on an ultimate choice based on a price comparison, to look for the most viable candidate from an economic standpoint. This is especially useful for determining the potential for upcycling waste materials. This approach is also interesting to introduce value analysis to students, which is a key component in circular product design.

It is important to note that any assessment of the end of life scenarios of a material or product depends greatly on the context in which it takes place. The economic viability of recycling operations is often precarious and transporting secondary raw materials over long distances is hardly justifiable. The initial analysis conducted here should therefore be part of a broader sustainability assessment, using, for instance, the 5-step methodology developed by Prof. Mike Ashby.

References

Elisa G. Ashton, Wilson Kindlein Junior, Yuri Walter, Mauricio Dwek & Peggy Zwolinski (2018), Identification of potential applications for recycled polymeric multi-material, International Journal of Sustainable Engineering, 11:6, 420-428, DOI: 10.1080/19397038.2018.1449030

Claes Fredriksson, Luca Petruccelli and Tomas Beno (2016), A Product-Centered Approach to Circular Economy in Design Education for Engineers, Proceedings of the 8th Conference on Engineering Education for Sustainable Development, EESD, Bruges, Belgium 4-7/9, 2016.

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ANSYS, Inc.
Southepointe
2600 Ansys Drive
Canonsburg, PA 15317
U.S.A.
724.746.3304
ansysinfo@ansys.com