Biomedical Waste: Health vs Environment

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Summary

The Bioengineering database of Granta EduPack offers the possibility to compare and select materials for various medical and biological applications. This is useful both for teaching students and for making materials decisions in the biomedical field. The Eco Audit tool included with the Bioengineering database also makes it possible to assess and compare different scenarios in terms of eco-design and end-of-life options.
In this advanced industrial case study, we explore how Granta EduPack can be used to discuss aspects of materials and waste in the healthcare sector. Both material selection for performance and clinical requirements as well as environmental consequences of disposable material and waste. To add realism, we visit the external ASM Medical Materials Database™ which contains over 60,000 approved medical devices.

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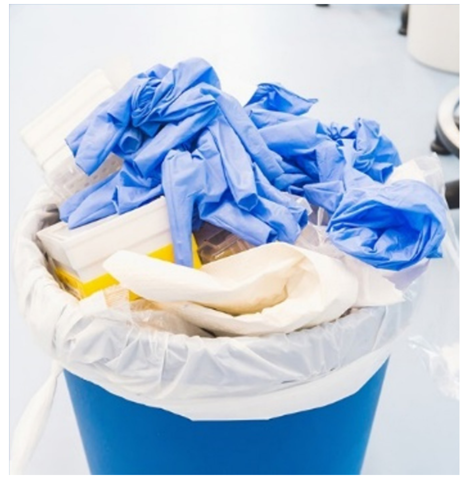
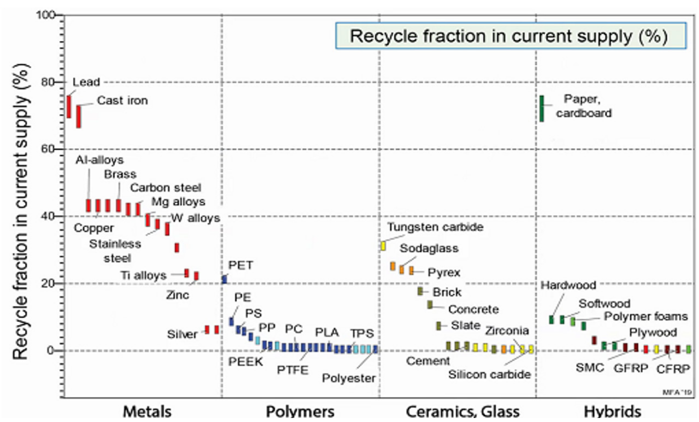
1. What is the scope?

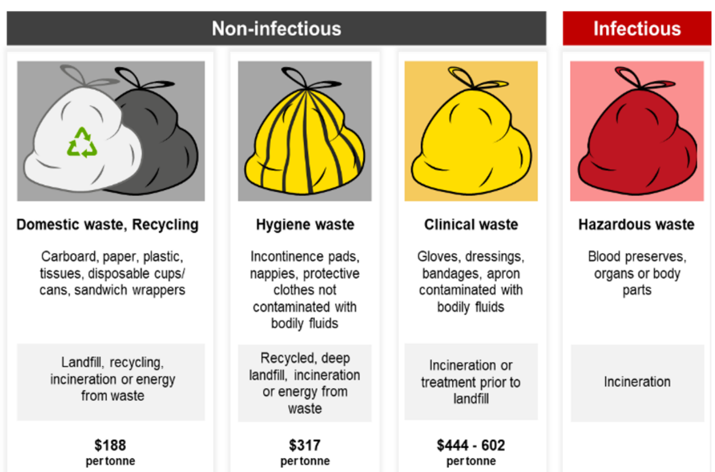


The healthcare sector and life-sciences in general are known to produce large amounts of waste; plastics, rubber, glass as well as metals. Some of these are considered biohazardous and can therefore not easily be recycled but are treated as disposable. However, of the total amount of waste generated by healthcare activities, about 85% is general, non-hazardous waste. The remaining 15% is considered hazardous since it may be infectious, toxic or radioactive. Protective clothing such as masks, gowns and gloves worn by doctors and nurses falls into this category and goes into bags. The average amount of waste created per hospital patient per day in Europe is around 3.3-3.6 kg (UK, France, Germany) and 8.4 kg in the US, with an additional 50 000 tonnes per year estimated to be generated by US home healthcare [B. Kaiser et al., 2001]. One relevant question to ask is if there is any chance of improving circularity in the biomedical sector?



In the UK, clinical waste is divided into four categories by the NHS: Infectious, Sharp, Redundant Medical Waste, and Anatomical. According to WHO, the infectious fraction is the most voluminous. Sharp objects, like needles and blades are mainly metallic with minor parts of other materials. These cannot usually be reused (sterilized) because they would need to maintain the sharpness from their pristine state. Normally it is considered infectious because of their invasive character but no energy can be recovered by incineration.

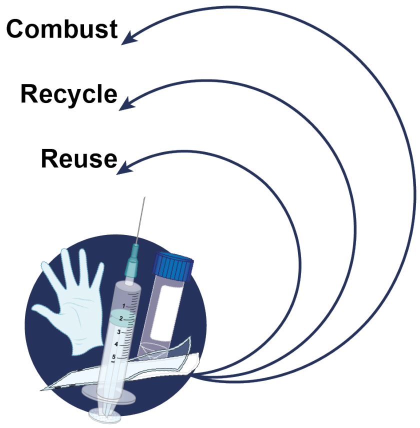
Plastic packaging and wrapping for sterile equipment could, of course, theoretically be recycled, provided they are separated into their polymer fraction to avoid contamination and that they are not mixed with infectious material. This is problematic in most clinical situations, where they come into contact with surgeons or nurses that might indirectly infect the material, e.g., in an operating theater. Rubber gloves, whether latex, silicone or polyurethane, are thermosets and cannot be recycled as materials. They have to be incinerated, possibly with energy recovery. Glass, if handled properly and if not contaminated by other materials, can be re-melted at high temperature, and be recycled or downcycled.



Adapted from report: *https://www.rcplondon.ac.uk/projects/outputs/less-waste-more-health-health-professionals-guide-reducing-waste*

- **Functional**
- **Economic**
- **Legal**
- **Hygienic**

There are many aspects that determine a products life, some relevant ones are shown to the left. Of course, the first life ends when the product fails and cannot perform its function. Budget restrictions may affect what is considered the economic life but, in the healthcare sector, there are also legislation and regulations that control end-of-life options and hygienic requirements that may prevent circularity of such products.



Circular economy developed when the importance of lost raw material value and the environmental damage caused by disposable, single-cycle, products was realized [G.M. Kane et al., 2018]. However, introducing circular economy principles in the biomedical sector is challenging because of the practical difficulties to sort mixed materials and the risk of infection. Realistically, only the options shown to the left exist. Some of the difficulties can be addressed at the design stage with the selection of more standardized and recyclable materials, better labeling and less mixed material products. The designer might also want to explore the potential for improvements regarding, for example, energy use and carbon footprint of these products in different life-cycle scenarios. Many products are already reused, following sterilization.

This case study makes use of the Bioengineering database of Granta EduPack which includes both tools for material selection and to assess life-cycle performance and options in terms of energy and carbon footprint.

2. What can EduPack do?

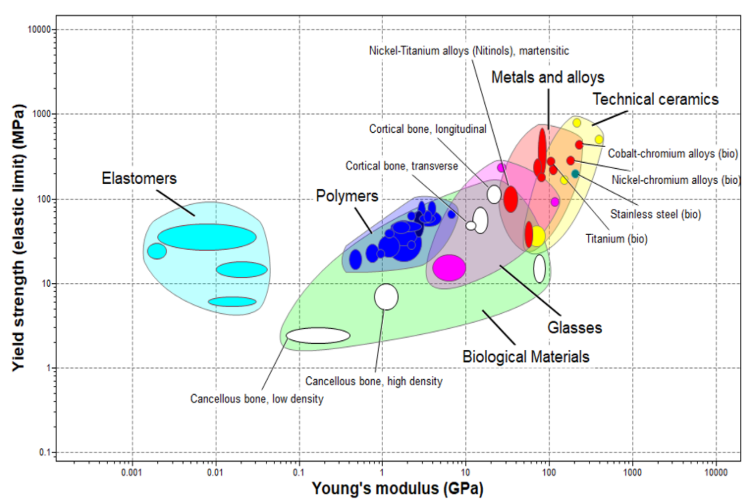
EduPack has relevant materials data for biomedical applications as well as for consumer products, both at Level 2 and Level 3. Level 2 is less overwhelming for students and suitable for learning about material properties and selection. The Bioengineering Level 2 database, however, is extended with bio-related materials. This more than doubles the basic Level 2 materials data-table, resulting in 251 datasheets. The Bioengineering Level 3 database of EduPack contains data records for over 4000 materials with a full range of alloys and grades to provide data for realistic projects in biomedicine or engineering. Some bio-specific properties are also added to both Levels 2 and 3 of the Bioengineering databases. Furthermore, there are tools for material selection, such as the Performance Index Finder, as well as the Eco Audit life-cycle tool to assess and compare different scenarios in terms of materials and end-of-life options.

Examples of basic materials in biomedical waste (Level 2):

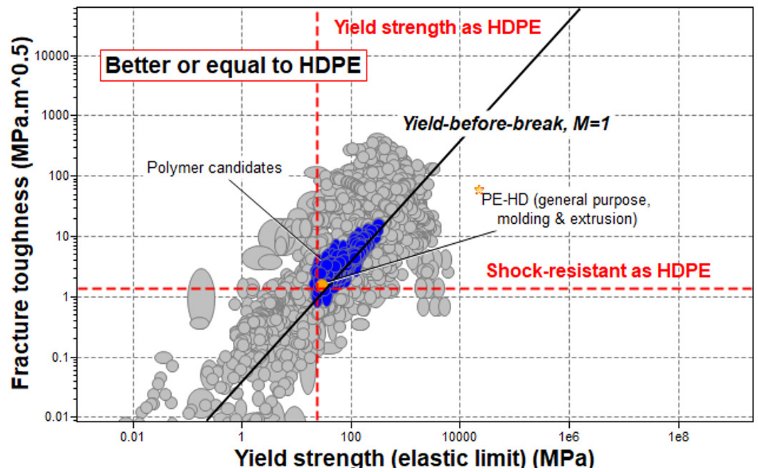
- Soda-lime glass
- Polyethylene (PE)
- Polypropylene (PP)
- Polystyrene (PS)
- Latex
- Silicone
- Cotton
- Stainless steel
- Paper

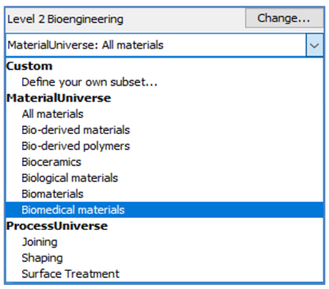
Examples of biomedical waste products:

One great feature of the Bioengineering databases is that they allow for property charts which simultaneously include both engineering materials and bio-related materials, such as the subset of Biomedical materials, to represent suitable candidates. An overview chart of any property in the database can easily be created, which covers the relevant materials. This can be done, both at Levels 2 and 3. These charts can then be used to compare and explain properties as well as to select compatible materials employing the systematic methodology developed by Ashby et al. with interactive, visual selection tools. Here is a Level 2 Bioengineering example.



The selection tools can be used to improve some aspects of a certain product by finding materials with better values for specific properties. For instance, if tougher polymers to replace High-Density Polyethylene (HDPE) is desired. A plot at Level 3 of key properties will guide the decision and deliver an overview of potential improvements. The black line indicates the performance index (M) for non-brittle failure. For liquid and gas containers, a yield-before-break material is preferred (above the line) since failure by fracture is most likely catastrophic.





Regarding the design of biomedical products, EduPack offers a wide range of support for material selection. There are both health-related properties, and eco-properties as well as estimated costs that can be used to make decisions. Consider a *vial for biomedical samples*, for instance. In order to follow the systematic selection methodology, a selection can begin with the subset of all *Biomedical materials* at Level 2, then removing unsuitable materials with additional screening, and finally to consider one or more performance indices for ranking of candidates. The *Function, Constraints and Objectives* for the vial can be:

Function – Container for liquids, must sustain compressive load from gripping forces without deformation, so Stiffness-limited design assumed; the stiffer, the better.

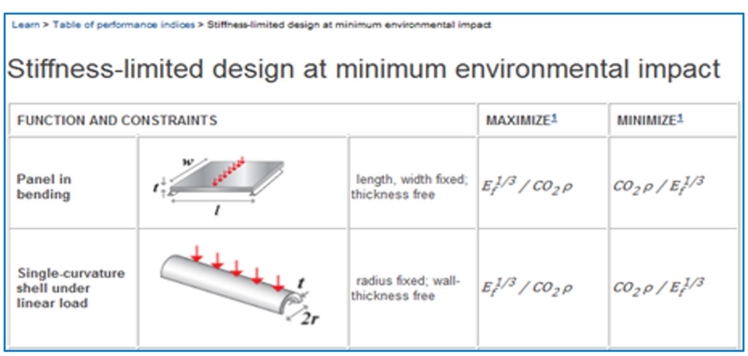
Constraints for the container:

- Biomedical material, durable in water
- Unfilled grade, not opaque

Objectives for the container:

- Primary; minimize carbon footprint
- Secondary; minimize cost

Vial for biomedical samples



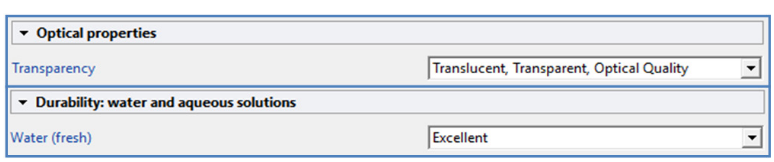
Learn > Table of performance indices > Stiffness-limited design at minimum environmental impact

Stiffness-limited design at minimum environmental impact

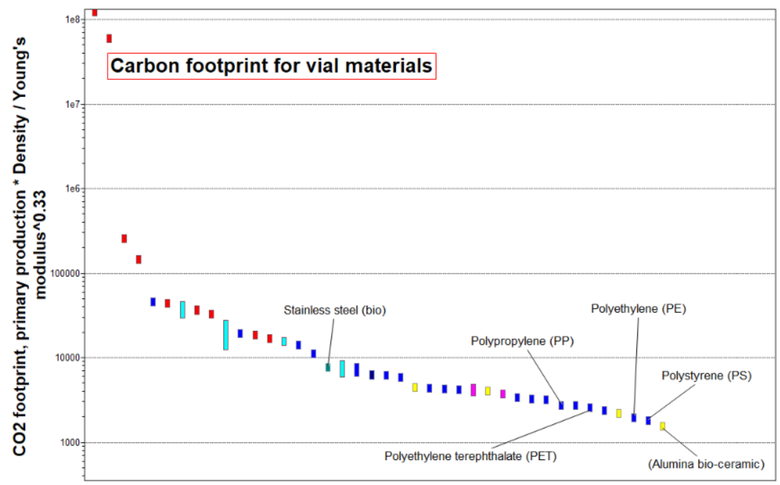
FUNCTION AND CONSTRAINTS			MAXIMIZE[1]	MINIMIZE[1]
Panel in bending		length, width fixed; thickness free	$E_f^{1/3} / CO_2 \rho$	$CO_2 \rho / E_f^{1/3}$
Single-curvature shell under linear load		radius fixed; wall-thickness free	$E_f^{1/3} / CO_2 \rho$	$CO_2 \rho / E_f^{1/3}$

The *Function* determines which performance index to plot on the axes of the property chart for visual selection. In this case, sufficient strength can easily be obtained by adequate thickness of the walls. A Stiffness-limited design best reflects the desired performance in terms of a rigid vial for a good grip (stiff, not flexible). The Learn button on the menu contains a Table of *Performance Indices*, with an option to minimize CO2-footprint.

It turns out that a tubular shape has the same index to minimize as a panel in bending. To investigate, in Level 2, we can use Young's modulus instead of flexural modulus, E_f. The *Limit* stage to the right, is used for constraints.



The results show the environmental performance for the biomedical materials. Alumina and Silicon have the lowest emissions but are greyed out as the opaque materials are excluded. Polylactide, PLA, is an interesting option, since it is both derived from renewable resources (such as corn) and biodegradable, but it has limited durability in water, which for this application is disqualifying. The two best options, PS and PE are both commonly used polymer materials for vial containers and caps, as is PP.

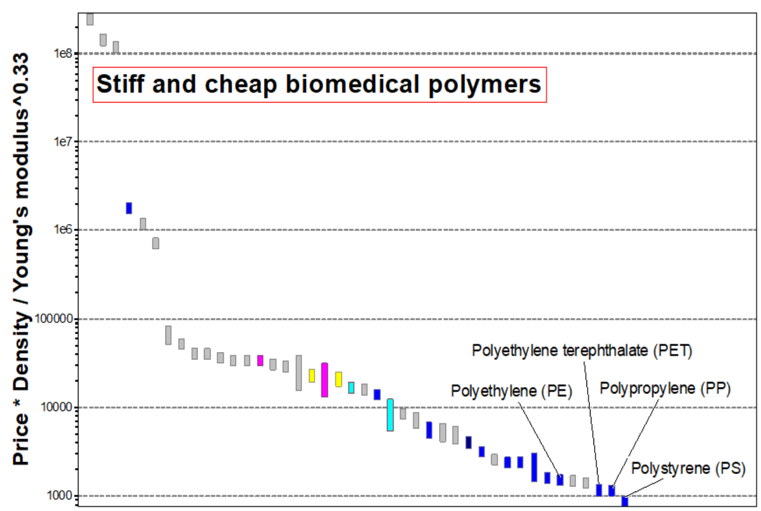


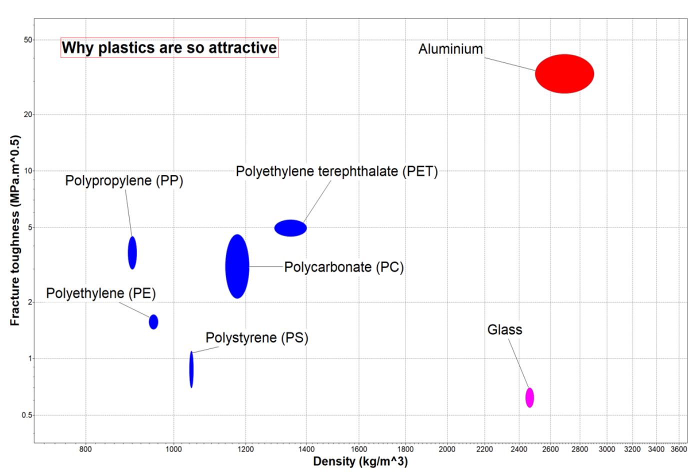
Rank by: Stage 3: Price * Density

Name	Price * Density
Polypropylene (PP)	1.04e3 - 1.16e3
Polystyrene (PS)	1.14e3 - 1.41e3
Polyethylene (PE)	1.33e3 - 1.38e3

A second objective, like cost, can be added on the second axis, or in a separate property chart, coupled with the first one. If only the price per volume, obtained by multiplying the price, C_m [$/kg], by the density, ρ [kg/m^3] is plotted, PP is the cheapest of these three. The ranking for different criteria can be seen explicitly in the *Results* window to the left in EduPack.

For a proper comparison, however, the full performance index must be used. This takes into account, not only density, but also how well the material delivers on stiffness. If this cost performance is plotted for the remaining materials, PS appears, slightly cheaper than the other previously considered polymers. Although PET is not commonly used for biomedical containers, it has many of the attractive properties for a vial; good mechanical properties to temperatures as high as 175°C. Crystal clear, impervious to water and CO_2. It is tough, strong, easy to shape and sterilize - allowing reuse.

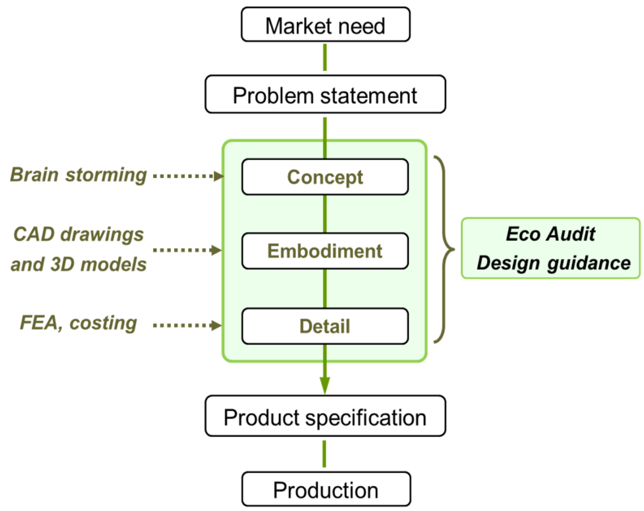


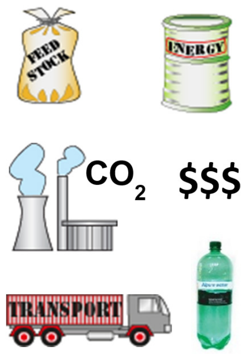


Bubble charts are useful when several properties are compared at the same time. When considering materials for a vial, it is easy to see why plastics have come to replace glassware, not only for its low cost. Polymers, in particular the biomedical candidates discussed above, are considerably lighter than glass. This is due to both higher fracture toughness, allowing thinner walls, and lower density of the material itself. Glass is attractive if reused many times and not transported long distances. High density is one relative disadvantage that PET has in comparison to the other polymers.

3. What can the Eco Audit tool do?

The Eco Audit tool has been developed to support the early product design process (see image to the right), where an estimate of eco-properties over the whole life-cycle is desired. This information can then be used to explore different scenarios and optimize the environmental performance of the product. It is also useful to re-design or assess existing materials from a standard requirements or legislative point of view as well as for cost minimization. It performs a streamlined Life-Cycle Inventory (LCI), rather than a full Life-Cycle Assessment (LCA). It is mainly concerned with estimating two of the most important parameters; the energy use [MJ/kg] and the carbon footprint [kg CO_2/kg] per kg of material over the life.





The reason for this simplification is that you can perform life-cycle investigations earlier in the design process and you can also save time, since it is now possible to compare different designs or end-of-life scenarios much easier. The inherent uncertainty of generic environmental data has to be acknowledged, though. EduPack contains many of the parameters that are needed. In addition to eco-properties of materials and processes (CO_2-emissions, energy, water consumption), emissions for various types of transports (trucks, shipping, air freight etc.) and cost estimates. It is product-centred, so the user needs to supply a Bill-of-Materials (BoM) including manufacturing processes, and to specify use phase as well as logistic information necessary for the assessment. The main parameters are shown to the left, where feedstock represents the materials.

As an example of an Eco Audit, we can use the vial described in the previous section. A typical base material is polystyrene (10 g) with a polypropylene cap (3 g), possibly with a thin silicone washer, so light that we will neglect it here. A hypothetical transport from Asia to somewhere in the UK is included.

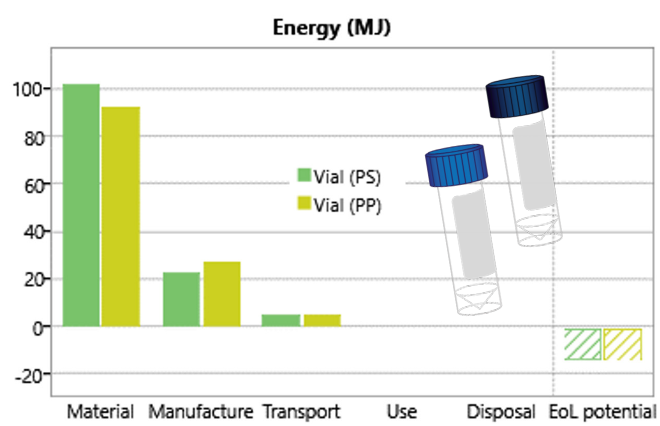
Material, manufacture and end of life

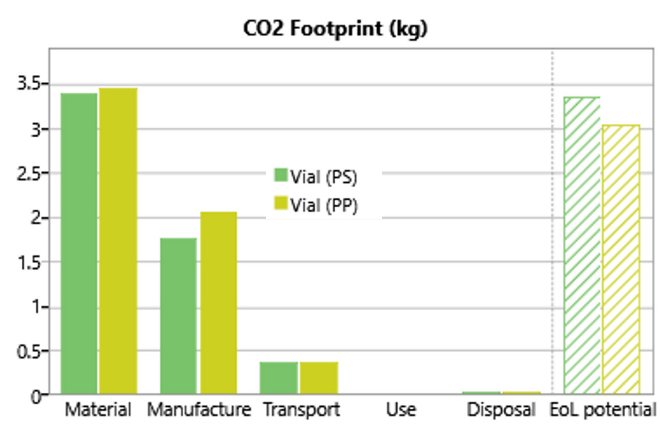
Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	End of life
100	Cap	Polypropylene (PP)	Virgin (0%)	0.003	Polymer molding	Combust
100	Vial	Polystyrene (PS)	Virgin (0%)	0.01	Polymer molding	Combust

Transport

Name	Transport type	Distance (km)
Ship Shanghai-UK	Ocean freight	2.2e+04
Lorry UK	14 tonne (2 axle) truck	100

Using the "*Compare with…*" function, another scenario, such as Polypropylene base with HDPE cap is added.



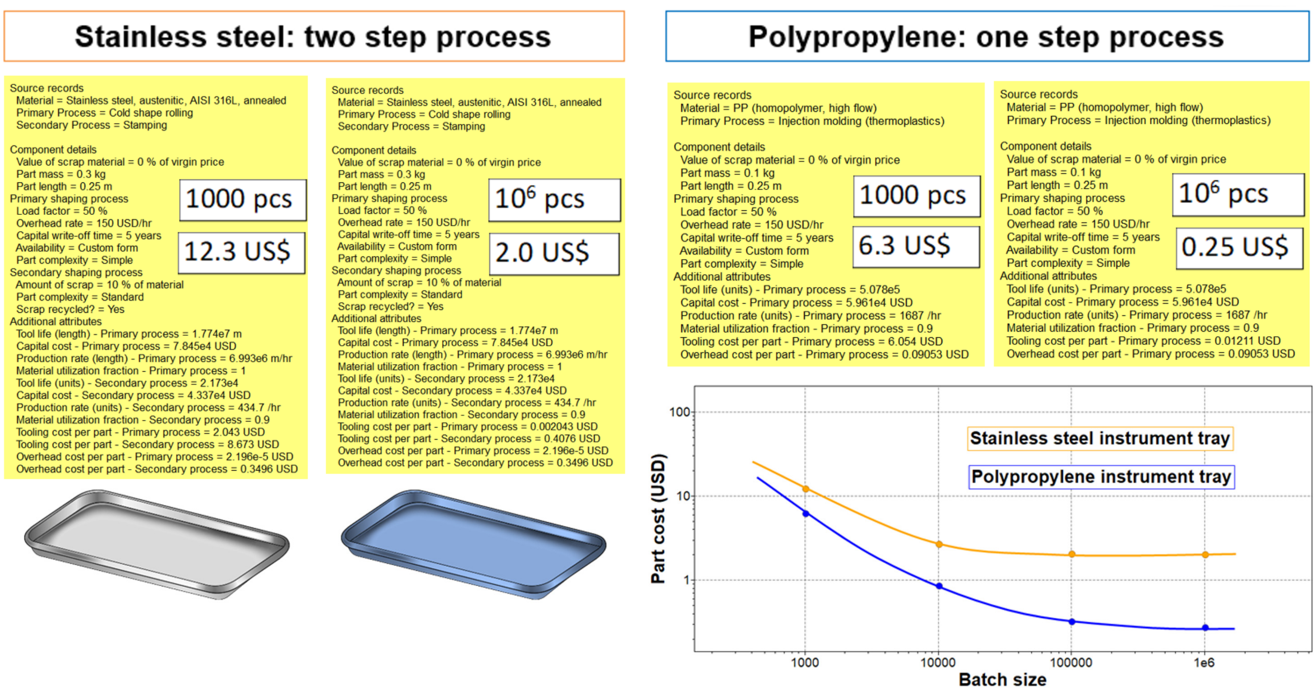


These output bar charts are created using the *Summary* chart button at the bottom of the screen. If more detailed numerical information is needed, a *Detailed report* button can be used. This report contains a breakdown of energy use and CO_2-emissions for each material in the BoM and each phase of the life-cycle.

In this example, the Eco Audit indicates that polypropylene (with HDPE cap) would have lower embodied energy but slightly higher carbon footprint in the material phase than polystyrene (with PP cap). Polystyrene has slightly lower values for both energy and CO_2 in the manufacturing phase. This is assuming that the vials and caps are produced having the same comparable masses. Virgin polymers have been assumed and combustion at the End-of-Life (EoL). If combustion is chosen at the EoL, the carbon footprint will include the CO_2 emitted during the incineration. The EoL potential indicates the hypothetical gain in the next life, if the materials are recycled instead of new. We can thus check the potential benefits of recycling instead of incineration. Different options for materials, logistics and disposal can easily be compared and benchmarked for design or re-design.

4. The part cost estimator

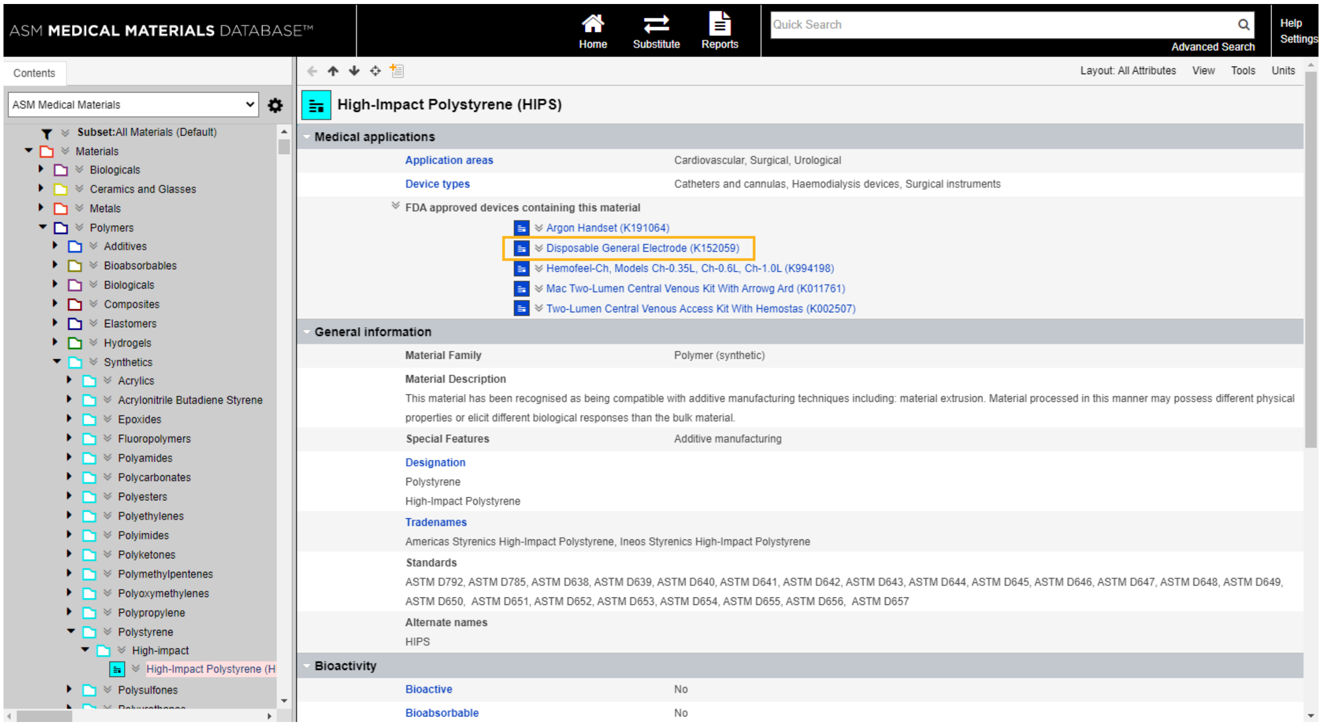
Another powerful tool for comparing design options is the *Part cost estimator* within the *Synthesizer tool* in the Bioengineering Level 3 database of the software. This addresses the important aspect of costs during the concept phase, including estimates of both the material and a set of standard manufacturing processes. The cost per part can be assessed for various production volumes, assuming a simple 5-term economic model described in detail in the embedded information. It enables comparisons of plastic disposable products manufactured by molding with metal alternatives produced by deformation processes and intended for sterilization and reuse. For example, a simple tray or pan, used in patient care, as shown below.



The *Part cost estimator model* delivers a set of material records for a range of different batch sizes. In the Bioengineering Level 3 database these contain the essential data that can be plotted within software. The results estimate how much cheaper the plastic is, which can then be used to assess how many times the steel tray needs to be reused to recover the initial cost (this gap increases with production volume).

5. Reality check

More specialized information for biomaterials, such as surface properties and sterilization, can be found in the ASM Medical Materials Database, accessible via the Bioengineering Edition of EduPack with the appropriate subscription. It also contains information on over 60 000 FDA-approved medical devices. Below is an example record of *High-Impact Polystyrene*, notice its use in an approved FDA device for disposable general electrode.



The coronavirus pandemic has, of course, accelerated a growing waste concern in the healthcare sector and brought the use of single-use PPE, such as disposable masks, to the forefront of discussion. Early research has estimated 3.4 billion facemasks are discarded each day, equating to 1.6 million tons/day [N.U. Benson et al., 2021].

What circular action is currently being taken? Examples below:

- A total of 1380 kg instrument waste was collected from 3 Dutch hospitals in a pilot study, where 237 kg could be refurbished and returned to the hospitals and put back to use. This saved some $40 000.
- The American care consortium Kaiser Permanente implemented reusable linens and patient gowns which showed that it was possible to wash and reuse them 60 times.
- Ascent Healthcare Solutions showed that by reprocessing single use medical devices, saving 2150 tons of waste going to landfill as well as $138 million in supply costs.

6. What does Granta EduPack bring to the understanding?

In this case study, we have come to the following conclusions:

• Granta EduPack Bioengineering Level 3 database is useful to select and understand environmental and cost aspects of biomedical materials and consumables in the healthcare sector.

• We have seen examples of how environmental aspects can be brought in for the design of biomedical products as well as investigating their End-of-Life (EoL).

• The software was used to demonstrate how both the selection and the Eco Audit tools work as well as the part cost estimator of the Synthesizer tool at Level 3.

• The ASM medical materials database can be invoked from within the software, provided subscription.

Use and Reproduction

Document Information

This case study is part of a set of teaching resources to help introduce students to materials, processes and rational selections.

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