Teaching Circularity using CES EduPack

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1. INTRODUCTION

In a *linear* economy (as opposed to a circular), manufactured products are central to prosperity and growth. The global material and energy flows resulting from this paradigm have, however, resulted in an unsustainable situation, with urgent issues, such as global warming and depletion of resources. In order to understand the consequences of consumption and minimize its impact, life-cycle thinking has been introduced for manufactured products. This holistic thinking is needed in many resource-related courses of Engineering, such as design, manufacturing and product development.

The product life-cycle phases are used in a traditional *linear* cradle-to-grave model to assess and minimize, for example, energy use or emissions over the product life-cycle. In particular, the flow of materials has followed the open-loop or *take-make-use-dispose* pattern, where they are transformed into products to be discarded after use, as shown in *Fig. 1*. The main life phases are: Material production, Manufacturing, Product Use and Disposal with the addition of the total contributions from Transports.

Furthermore, resources are getting more and more constrained, with an estimated 3 billion new consumers to enter the market in the next 20 years [1]. The majority of these requiring the same living standard (and resources) as the current middle class [2]. Also, the downwards trend in material prices ended at the beginning of the 21st century, and now displays higher volatility [3]. This provides an incentive to increase resource efficiency, where materials flow in a closed loop (*cradle-to-cradle [4]*), in a more circular materials economy. Future engineers will be a key part of this transition.

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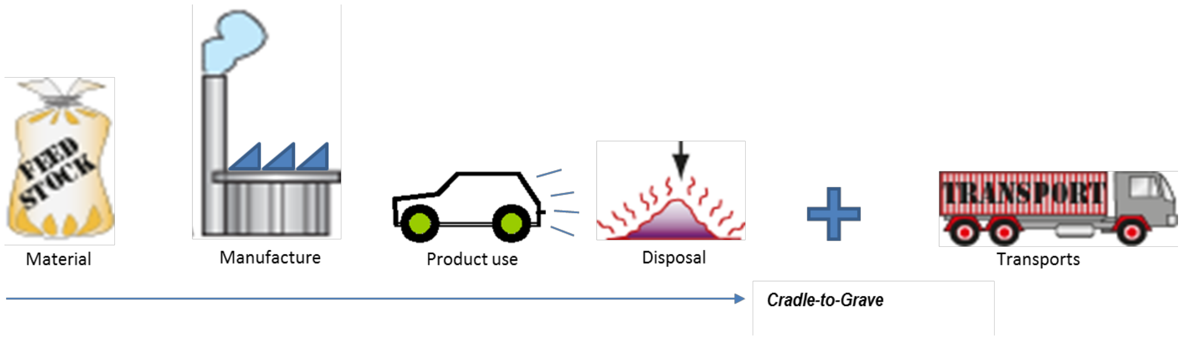

Fig. 1. Phases of a linear cradle-to-grave product life-cycle (of a car), considering: Materials production, Manufacture, Use and Disposal, as well as total Transports.

In a *circular* model, materials remain a valued asset to be conserved for reuse [5,6]. It also implies the use of renewable energy, material tracking (quality and location), and designing products that aid with the material restoration and reuse.

A manufactured product hence needs to be considered over several life-cycles. These lives, or loops, can be analysed in terms of mass flow, as well as in terms of energy use, carbon emissions or cost. An Eco Audit, is an established streamlined Life-Cycle Inventory (LCI) used in undergraduate teaching and in industry, for conceptual design of products. This tool, part of CES EduPack and with access to vital materials and process data, can be used in courses on materials or sustainability to support learning outcomes in the CDIO syllabus and for accreditations, as described elsewhere [7]. In this paper, we demonstrate how it can help students to analyse and understand important aspects of circularity in engineering courses. The product life-cycle phases in a *circular* context for a family car can be seen schematically in *Fig. 2*, below.

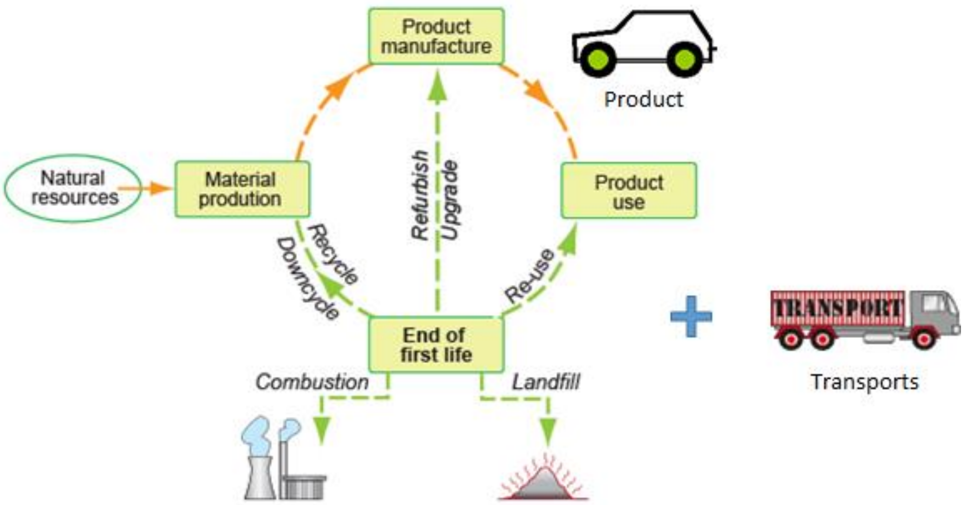

Fig. 2. Model of product-centered life-cycle phases, with end-of-life options for a car

2. CIRCULARITY AUDIT

In an open loop, materials used as feedstock (raw materials or input) to the manufacturing of a product are of one kind: *virgin material*. Moreover, as the material is disposed into landfill, this is classified as *unrecoverable waste*. In a closed loop flow of materials, waste can become a feedstock via different routes, as shown in *Fig. 3*:

- Reuse (no waste)
- Remanufacture (Refurbishing/upgrading)
- Recycling/Downcycling
- Or, possibly, Transformation via biochemical processes (not shown)

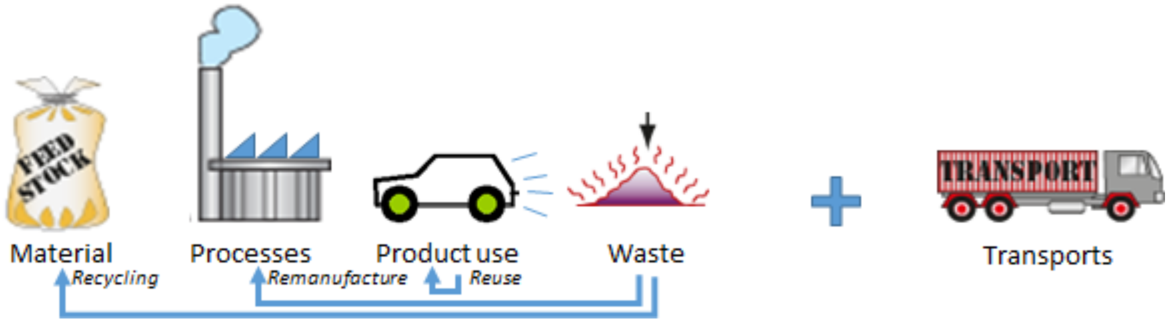

Fig. 3. Product life-cycle phases of an Eco Audit in the context of a cradle-to-cradle model centered around the product (a car) and avoiding waste to landfill.

In a Circularity Audit, scenarios can be analysed in terms of loops or lives that are studied individually starting with the first life of a product and subsequently various cases of additional life-cycle loops: Reuse, Remanufacture and Recycling.

3. MODEL CASES

Reuse is considered reintroducing a product for the same or another purpose in its original form, following minimal maintenance and cosmetic cleaning. If a product cannot be reused as a whole, individual components can be reused in a functional way. In this case, the total life-cycle energy and CO_2 Footprint of the product comes mainly from the use phase but there may be transport energy and carbon emissions associated with the transcendence into the next product life. The total cost of the product equals the second hand price, including possible transport costs.

Remanufacture is the process of disassembly and returning a product to a good working condition by using new material and/or functioning, reusable parts taken out of used products. This process includes quality assurance and potential enhancements or changes to the components of the product. In the remanufacture case, the total life-cycle energy and carbon arising from processes involved in replacing or repairing parts, in addition to the use phase and transport energy and carbon emissions, are taken into account. The cost of the product should also include these additional contributions.

Recycling is the process of recovering materials for the original purpose or for other purposes. The recovered materials feed back into the process as crude feedstock. In this case, the total lifecycle impacts should take into account the energy and carbon emissions derived from any additional recycling processes involved, as well as additional costs.

4. METHODOLOGY

4.1 Circularity Audit of a milk bottle

In this paper, we take the simple example of a milk bottle to showcase how carrying out a Circularity Audit using the advanced version of the Eco Audit (available in some CES EduPack editions). This example can be used in a lecture, assignment or project, to introduce students to the concepts of material circularity. In this first step, four linear reference scenarios (1-4) for a milk bottle are analysed to demonstrate basic concepts and thinking. Reuse in this case is just wiping the bottle and using it for a vase, eventually sending it back for remanufacture. Remanufacturing means collecting the bottle to the dairy factory for washing, refilling and re-sealing for sale and distribution back to the customer. Recycling consists of collection, sorting the glass bottle for re-moulding into a new bottle. Some data is taken from a full LCA of milk containers supported by an Eco Audit [8] but material and process data is contained within the software. Distances are specific to each case and are chosen as realistic examples. However, these can be tailored to any educational scenarios as needed.

The Bill of Materials for 100 milk bottles, each with a total mass of 0.41 kg (excluding the milk) is described in *Table 1*. The four linear cases are described in *Table 2*. The transport stages and use characteristics are described in *Tables 3* and *4*, respectively.

Table 1. Bill of materials for glass milk bottle.

Component	Material	Recycled content (%)	Part mass (kg)	Qty.	Process
Glass bottle	Soda lime - 0070	Virgin (0%)	0.41	100	Glass molding
Foil caps	Tin, foil	Virgin (0%)	0.0021	100	Rough rolling, Cutting and trimming
Milk			1	100	

Table 2. The four linear cases description of the first product life.

Model Cases (Loop / life description)	**Type of feedstock for glass bottle**	**Types of end-of-life for glass bottle**
1. Cradle-to-grave	Virgin	Landfill / Unrecoverable waste
2. Cradle-to-reuse	Virgin	Reuse (as vase)
3. Cradle-to-remanufacture	Virgin	Remanufacture (refill)
4. Cradle-to-recycle	Virgin	Recycle

Table 3. Breakdown by transport stage used in the analysis.

Stage name	Transport type	Distance (km)
Plant to distributor per day	14 tonne truck	30
Distributor to customers per day	Light goods vehicle	85
Customer to landfill	14 tonne truck	30
Customer to remanufacturing plant	14 tonne truck	115
Customer to recycling plant	Light goods vehicle	150

Table 4. Description of use, static mode employed in the analysis (energy for cooling of the milk bottle).

Energy input and output type	**Electric to mechanical**
Use location	Europe
Power rating (W)	50 (typical)
Usage (hours per day)	24
Usage (days per year)	5 (typical)
Product life (years)	1

The second step is to consider the case where a bottle has several use lives. In our example, the glass bottle is first used (refrigerated and consumed), reused for a second life as vase, then remanufactured for a third, and finally recycled after consumption in a final fourth life in our scenario. Each use phase of the product life is assumed to happen sequentially, as described below in Fig. 4 and relevant *Table 5*. We stress that these examples are shown as a demonstration of the feasibility to use CES EduPack for a Circularity Audit to enhance teaching, rather than to provide exact numerical values for these scenarios. It is the displayed potential as a tool for analysis, discussions and understanding that is the main outcome of this paper.

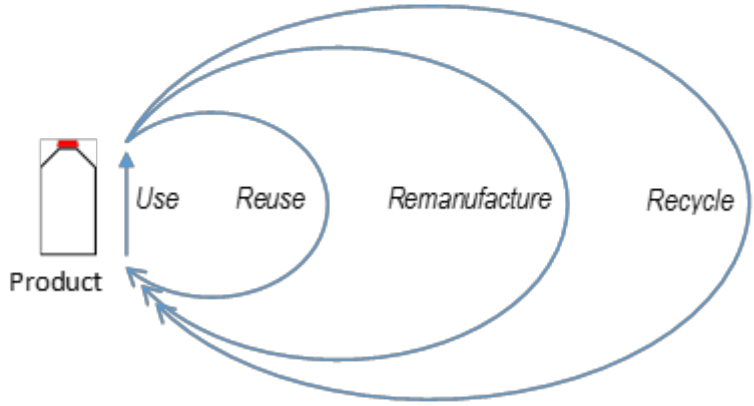

Fig. 4. Model for a product-centered four-life scenario (100 milk bottles).

Table 5. Description of product-life scenarios. *Feedstock reused: mass=0kg.

Model Cases (Loop / life description)	Type of feedstock for glass bottle	Types of end-of-life for glass
First life (use)	Virgin	Reuse
Second life (reuse)	Reused*	Remanufacture
Third life (remanufacture)	Reused*	Remanufacture
Fourth life (recycle)	Reused*	Recycle

4.2 Material Circularity Indicator calculation

The product level Material Circularity Indicator (MCI) measures the extent to which a product has minimised the amount of virgin material as feedstock and unrecoverable waste at end of life, and also how long and intensely it is used compared to the industry average. The latter comparison with industry is because the longer a product is used, or if it is used at a higher rate (for example a product shared vs bought per individual), the less materials is used over the same period of time. For more information on this indicator, background and theory behind the calculations, please see the paper available at the Ellen MacArthur Foundation website [9].

MCI values range from 0 (zero) to 1. The higher the MCI score, the better the materials of the product circulate. This value can be used to in an approach to improve the sustainable and efficient use of materials in products, for example in courses on product development and/or design for sustainability.

The equation for MCI_P of a product is:

$$MCI_P = 1 - \frac{V+W}{2M+\frac{W_F-W_C}{2}} \cdot F(X) \quad (1)$$

Where V is the fraction of feedstock from virgin sources, W is the unrecoverable waste calculated from the waste going to landfill, and also considers the average of waste generated in the recycling process W_C and the waste generated to produce any recycled content used as feedstock W_F. M is the product mass.

F(X) denotes how the lifespan and intensity of the product compares with the industry average, and for this case study, we are indicating it is the same, hence F(X) = 0.9 [9].

Since this is a new indicator for material circularity, it is not currently available in the Eco Audit tool within CES EduPack, hence the calculations are done manually.

5. RESULTS FROM ECO AUDIT AND MCI CALCULATIONS

The results of calculating energy, carbon emissions and MCI for each of the first 4 linear reference cases are detailed in the below *Table 6* and *7*, and graphically represented in *Fig. 5* and *6*. Key messages for students are indicated directly in the figures below.

Table 6. Energy and MCI results for linear model cases.

	Energy (MJ)					MCI
	Material	Manufacture	Transport	Use	Disposal	
1. Cradle-to-grave (landfill)	479	361	24	50.2	8.24	0.10
2. Cradle-to-reuse	479	361	20.4	50.2	8.24	0.55
3. Cradle-to-remanufacturing	479	361	34.2	50.2	8.24	0.47
4. Cradle-to-recycle	479	361	38.4	50.2	28.7	0.47

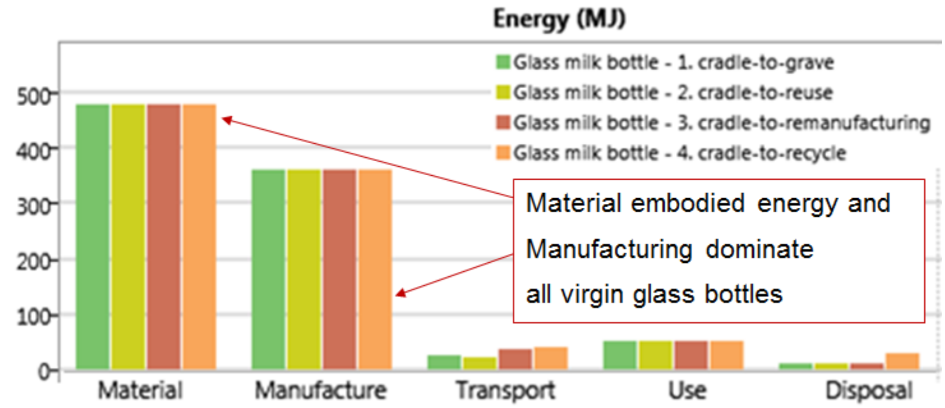

Fig. 5. Comparative Life Cycle Inventory of Glass Milk Bottle: Energy (MJ) comparing the four linear product scenarios using the advanced Eco Audit.

Table 7. Carbon footprint (kg) results for linear model cases.

	CO_2 footprint (kg)				
	Material	Manufacture	Transport	Use	Disposal
1. Cradle-to-grave	34.2	28.9	1.7	2.74	0.577
2. Cradle-to-use	34.2	28.9	1.45	2.74	0.577
3. Cradle-to-remanufacturing	34.2	28.9	2.43	2.74	0.577
4. Cradle-to-recycle	34.2	28.9	2.73	2.74	2.01

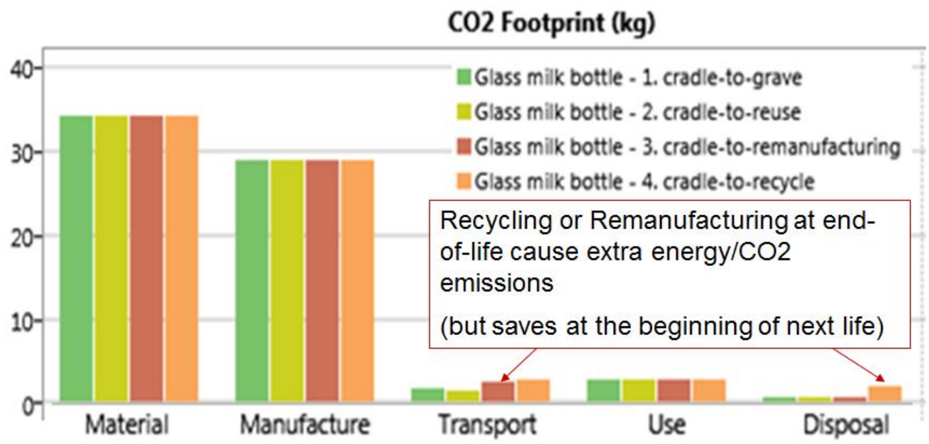

Fig. 6. Comparative Life Cycle Inventory of Glass Milk Bottle: CO_2 Footprint (kg) comparing the four linear product scenarios using the advanced Eco Audit.

The results of estimated energy, carbon emissions and MCI for each of the product life scenarios are detailed in *Tables 8* and *9*, and graphically represented in *Fig. 7* and *8*.

Table 8. Energy and MCI results for product life scenarios. *calculated separately.

	Energy (MJ)					MCI
	Material	Manufacture	Transport	Use	Disposal	
First life (use)	479	361	20.4	50.2	8.24	0.55
Second life (reuse)	0	0	0	0	6.6*	0.99
Third life (remanufacture)	45.6	0.144	31.9	50.2	0.043	0.95
Fourth life (recycle)	45.6	0.144	37	50.2	28.7	0.92

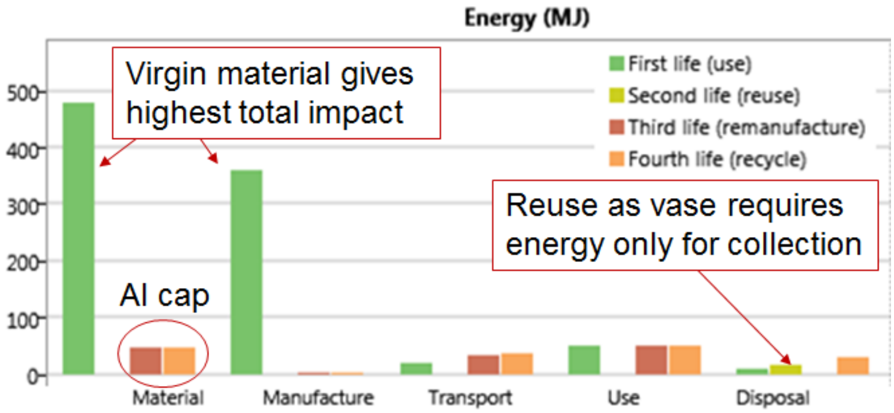

Fig. 7. Comparative Life Cycle Inventory of Glass Milk Bottle: Energy (MJ) comparing all phases of the four product-life scenarios using the advanced Eco Audit.

Table 9. Carbon footprint (kg) results for product life scenarios.

	CO_2 footprint (kg)				
	Material	Manufacture	Transport	Use	Disposal
First life (use)	34.2	28.9	1.45	2.74	0.577
Second life (reuse)	0	0	0	0	0.47*
Third life (remanufacture)	3.16	0.0108	2.26	0.342	0.00299
Fourth life (recycle)	3.16	0.0108	2.63	0.342	2.01

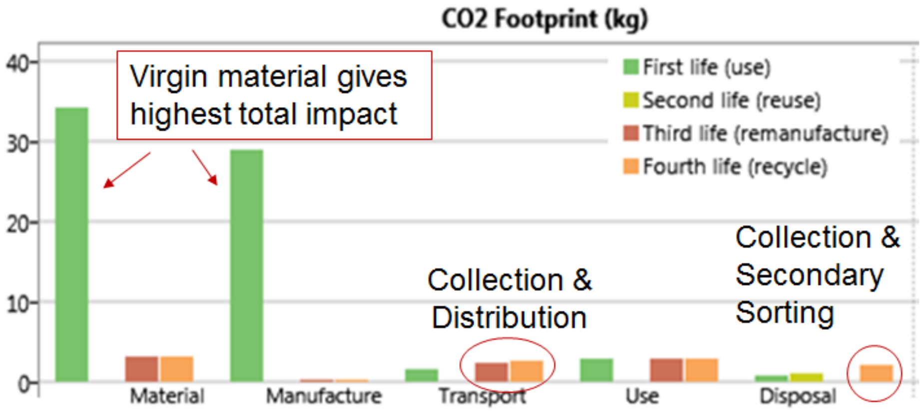

Fig. 8. Comparative Life Cycle Inventory of Glass Milk Bottle: CO_2 Footprint (kg) comparing all phases of the four product-life scenarios using advanced Eco Audit.

6. RESULTS AND CONCLUSIONS

From the examples and results above, it is clear that this case study of a simple milk bottle allows one to carry out successive and informative lifecycle inventories, where the energy, carbon footprint and MCI can be compared. The results show that different product life scenarios will deliver data for discussions in class (or by students), for example the effects of reused feedstock and remanufacturing on the MCI or the relationship between MCI with the low energy use and CO_2 Footprint.

Requesting students to provide an analysis of similar scenarios in order to explore the concepts of reuse, remanufacturing, recycling as well as using different materials as input for the product or minimising unrecoverable waste at end of life of the product, promotes the understanding of material circularity, and can be assessed against learning outcomes related to sustainability.

Based on the case study presented in this paper, we have showed that is possible to use the Eco Audit tool to enable the comparison of linear and closed loops of materials, in order to help students learn more about product life options. This helps engineering students to be aware on how design decisions will influence the flow of materials, especially if we are dealing with constrained resources. For instance, in Design for Sustainability and in Product Lifecycle Management.

For future work, this methodology should be evaluated in the classroom, where the concepts can be put to the test. Further studies could include also cost considerations.

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