Efficient LCI Data Exchange for Approximate LCA in Industry

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Abstract

This paper looks at the problems associated with shortening product development cycles and carrying out life cycle assessments (LCAs) during the design process. LCA is most effective during the early stages of the design process, due to the low cost of change and the high impact the concept stage has on the whole life cycle. The difficulties associated with carrying out LCAs during the concept stage are related to the low definition of the design. The resulting paradox of wanting to be able to carry out LCAs early and having a relative undefined design has been addressed by representing the life cycle inventory (LCI) as relationships to design parameters. This approach is used in combination with a database and a LCA model, where the component manufacturers enter the data used to establish LCI models. These LCI models are used to determine the approximate LCI and a subsequent order-of-magnitude LCA can be carried out. The approach is suitable for large enterprises with a large number of suppliers, where the database is administered by the large company, and for small and medium sized enterprises (SMEs), where the database is administered by a third party. The paper introduces the concept and a prototype software is briefly illustrated.

1. Introduction

Life cycle assessment (LCA) is the breakdown and investigation of the whole life of products and services with respect to financial and environmental impacts of the various life cycle stages. These comprise of the following major stages (adapted from [1, 5, 6]):

- Pre-Use
  - Pre-manufacture
    - Raw Materials Acquisition
    - Bulk Processing of Raw Materials

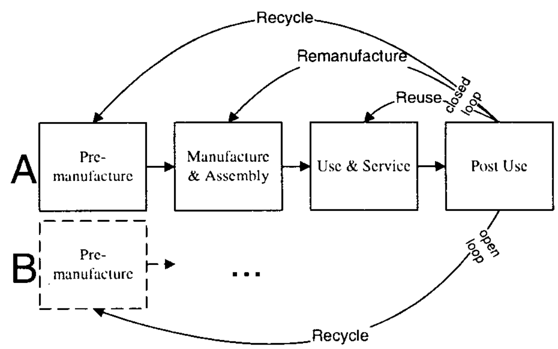


Figure 1. Simplified schematic of Life Cycle Stages illustrating recycling (open- and closed-loop), remanufacturing and reuse.

  - Manufacture and Assembly
- Use
- Post Use
  - Retirement (Recycle, Remanufacture, Reuse)
  - Final Treatment and Disposal

In **Fig. 1** a simplified schematic outlines the stages of the life cycle. The life cycle is simplified to degree which is of use to the LCA analyst within the early stages of the design process.

For a complete life cycle assessment the analyst has to iterate between the following phases (see also **Fig. 2**)

Goal and Scope Definition [4, ISO 14041] sets the goal of the LCA and defines the limits of what the LCA should capture [9, 11].

Inventory Analysis [4, ISO 14041] of LCA is well established and describes the in- and outputs of processes in terms of materials and energy.

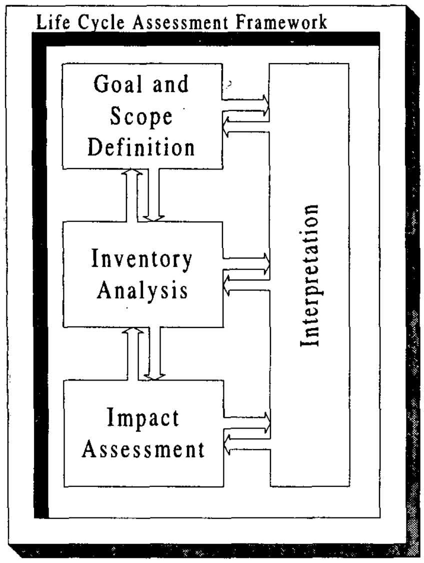


Figure 2. The LCA Framework according to ISO 14040 (adapted from [4])

Impact Assessment [4, ISO 14042] is the phase where the relative importance of different emissions are related and without guidance a suggested 'improvement' could make things worse (Environmental Impact Analysis (EIA) in Life Cycle Assessment).

2. Simplifying LCA

To carry out a full LCA on even a simple product means that the analyst has to gather inventory information on all the processes that the product and any parts of it comes into direct and indirect contact with. Determining this Life Cycle Inventory (LCI) is the most data intensive and costly process of LCA. The LCI of a complex product will consist of thousands of unit processes with 10^4 to 10^5 or more numerical data elements [2]. This emphasises that it is vital to 'compress' information into manageable entities. And thus the complexity of full LCA's usually limits studies to scientific bodies or to large industrial companies [3]. It is therefore important for LCA's to become more widespread to develop abridged or streamlined LCA (SLCA) methods.

To reduce the data and time required for an LCA has lead to the emergence of Streamlined Life Cycle Analysis (SLCA) methods. Most of the streamlining approaches are based on reducing the complexity of an LCA by leaving out those stages of the life cycle which are shown to have the least impact on the total life cycle (horizontal incompleteness) or by not taking into account higher order processes (vertical incompleteness). The difficulty with this approach is that the analyst has to first show that the effect of leaving out certain information has little effect on the outcome before the information can be left out. This may be achieved by comparing the case to a similar but known situation or by approximate calculations. There is still a large amount of information required to carry out even a SLCA.

The main motivation for streamlining LCA is to accommodate the difficulties associated with conducting full LCAs. The difficulties mainly arise in the areas of accessing relevant inventory data, for the various life cycle phases of the product. The methods used by LCA practitioners for streamlining the LCA process can be divided into several groups [10]. They include the following quantitative approaches:

Eliminating life cycle stages Upstream and/or downstream stages of the life cycle are removed.

Eliminating specific inventory parameters Depending on the impact category that is of interest, certain inventory parameters are included, while disregarding other inventory parameters. E.g. if the impact of concern is global warming, then greenhouse gasses are investigated.

Limiting or eliminating impact assessment Impact assessment is often not addressed and the objective becomes a minimization of the emissions as opposed to the minimization of the impact ('less is better' interpretation).

Using surrogate data When data on a particular material or process cannot be found, then the data of a similar material/process is used.

Limiting constituents to a threshold quantity Thresholds are used in full LCAs. If a constituent is below a certain threshold it is not included in the LCI. In full LCAs this threshold is often 1% (rule of thumb) of the life cycle total and in streamlined approaches this can be increased to 5% or 10%.

Focusing on specific environmental impacts or issues The scope of a LCA is to focus on a specific environmental impacts or issues, determined by expert groups or the sponsor. Often the focus is on those impacts for which data is available, or on issues important to the organisation.

Qualitative approaches:

Using qualitative data In cases where quantitative data is not available, a qualitative evaluation relies on expert judgement to determine the importance of various environmental concerns for each product or process.

Establishing "showstopper" or "knockout" criteria
Focuses on specific issues where the criteria leads to an immediate decision. E.g. the issue can be "is any ozone depleting substance released during the life cycle?" If the answer is positive, then the solution is disregarded.

Each of these approaches risk the exclusion of significant impacts, but as industry can only utilise practical methods, LCA practitioners use one or a combination of the above to obtain a result with the resources available. The results obtained using SLCA approaches have to take into account the limitations.

In a strict sense, even the 'most complete' LCA is a streamlined LCA, since most (if not all) detailed LCAs of complex products rely on 'regional[1] and temporal[2] surrogate data' for raw materials and processes and constituents are limited to a threshold quantity (rule of thumb: 1% by volume or mass, see above list).

3. Current Approach

3.1. Outline

The approach used in this paper is based on a parameterising approach. Mass produced (engineering) components — such as complete products (e.g. 3-phase induction motor) and parts (e.g. rolling element bearings) — are analysed and parameters are determined which are related both to the Life Cycle Inventory and to the design (see [7, 8] for details).

In summary the approach comprises of two steps distinct from previous approaches:

Parameterised Inventory. The *material composition*, the *manufacturing inventory* and the *retirement inventory* is established in average relative terms, e.g. as specific inventory per unit product mass, so that product mass is the relating parameter to the inventory. This represents the *average product mass specific inventory*.

Component Models. The inventory related parameters (e.g. mass, efficiency) are related to design parameters. These relationships are determined by theoretical and empirical means.

Further models required for sizing of the component during the design process are included. These additional component models are based on the various engineering sciences, e.g. thermodynamics, rigid body statics, kinematics, dynamics, hydrostatics, fluid dynamics, etc., often with applied assumptions and thus simplified for specific components.

The *average product mass specific inventory* represents the most common material composition for the product range, and these representative products should be analysed as thoroughly as possible, so that general conclusions regarding its relative material composition can be drawn with some confidence.

This approach represents within the streamlining approaches the use of *surrogate data* at the point when the inventory data is used for a concrete product LCA. In order to avoid the exclusion of significant impacts the above mentioned streamlining approaches should be used with great care when establishing the parameterised inventory, i.e. the *average product mass specific inventory* must be representative for the component.

The component's material composition is not included as single values, but as ranges, e.g. a lower and an upper limit or as a mean and an estimated deviation.

Furthermore significant variations within one product/component group can be included as an independent set of an *average product mass specific inventory*.

The last two points allow that during the carrying out of the LCA, it can be verified whether the difference in the material composition is of importance within the life cycle for a concrete design (sensitivity analysis).

3.2. Procedure

The method outlined here is currently being implemented into a software which allows designers to efficiently evaluate a product's life cycle in the early phases of the design process.

The database management system utilised for the component models and parameterised inventories is Microsoft's MS Access® and the computational environment employed is MathWorks' MatLab®.

Here the product is represented to comprise of several components as illustrated in **Fig. 3**, which are *linked* so as to represent the use-phase (example see **Fig. 6**) and the pre- and post-use phases. The use-phase is the part of the life cycle in which the product fulfils its function, and which must be seen as the reason for the existence of the product. Consequentially, modelling the use-phase in terms of parameters that relate to the inventory of one or more life cycle phases and defining the pre- and post-use phases (non-use-phase), allows the evaluation of the importance of chosen

[1] Inventory data on a material from one region is used while the material of the real product may come from an unspecified combination of regions

[2] The LCA is carried out for a product for a certain year, but often historical data for raw material and process inventories has to be used.

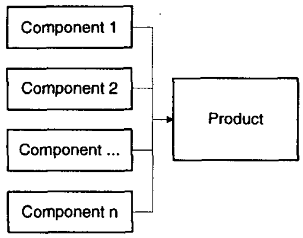


Figure 3. The product to be analysed is put together from components

design parameters on the life cycle inventory and thus on life cycle impacts and cost.

Once the use-phase is defined, a sizing module within the LCA/LCC system module can estimate the size of the components in terms of their mass. This is done via the Component Models, which include, among others, relationships for *Life Cycle Parameters*[3] (LCPs) — such as mass and efficiency — in terms of design parameters (DPs) [7],

$$LCP = f(DP_1, DP_2, ..., DP_n) \tag{1}$$

After the component sizing, the LCI can be estimated. Since DPs are directly or indirectly related to the LCI, a sensitivity analysis can be carried out, to estimate the relative importance of different DPs on the product's LCI and to LCA and LCC results. This potential for sensitivity analysis and optimisation is depicted in **Fig. 4** by the back-feeding arrows from the LCI and LCA/LCC evaluation to the component sizing subroutine.

Summarising **Fig. 4** the approach utilises databases which the LCA/LCC system module accesses. The novelty is the utilisation of databases for the

- Component Models and the
- Parameterised Inventories

This allows a flexible definition of especially the product's use phase, while minimising the work required to define the product's use phase. As mentioned before, defining the use-phase in relationship to design parameters allows the LCA/LCC system module to manipulate the design parameters, which is useful for sensitivity analysis and optimisation.

The dotted costing related components are not currently implemented, but may be added at a later point.

The component sizing subroutine requires the component models to be defined as

[3] I.e. the aforementioned parameters that relate to the inventory of one or more life cycle phases.

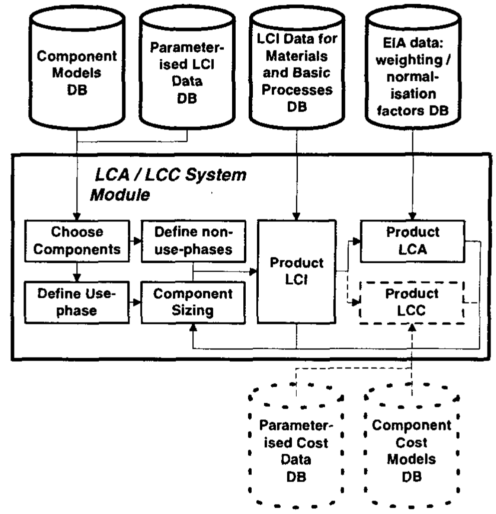


Figure 4. General Flowchart of LCA/LCC System Module and required databases

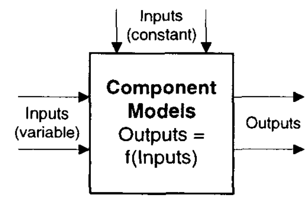


Figure 5. Component's models inputs and outputs

$$\text{Outputs} = f(\text{Inputs}) \tag{2}$$

where the various inputs can be constant[4] or variable[5] (**Fig. 5**). The variable inputs include time series data relevant to the use phase. The user selects design parameters (constants in **Fig. 5** with appropriate ranges) that can be manipulated by the LCI/LCA/LCC subroutines for the sensitivity analysis and optimisation. This is the strength of this method, since it allows the visualisation of the relative importance of design parameters on the life cycle.

[4] Constant during one use-phase simulation, but can be varied for another use-phase simulation, i.e. a parameter.

[5] Variable during one use-phase simulation.

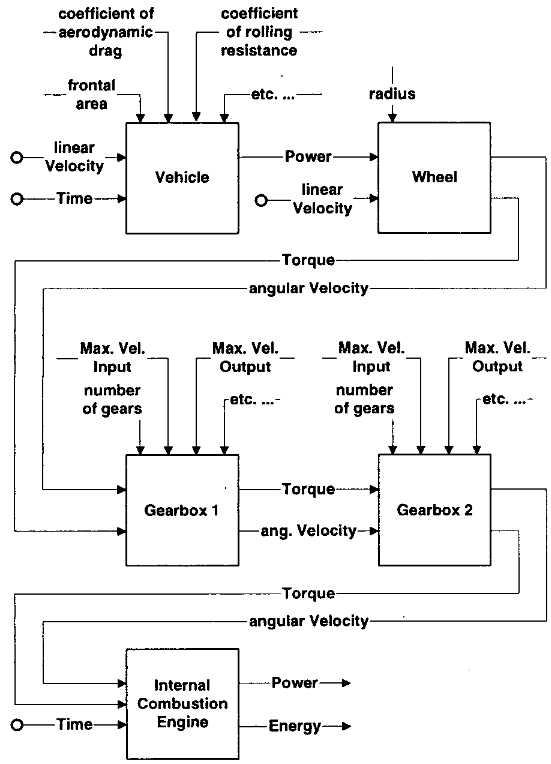


Figure 6. Example: Flowchart of a Vehicle illustrating linked Components for the use-phase

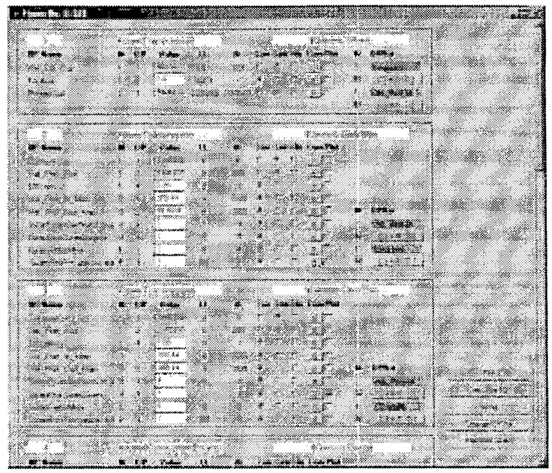


Figure 7. Part of the use-phase setup screen of the LCA/LCC system module for the example in Fig. 6

4. An Example

The specific example of a simple drive train for a vehicle briefly illustrates how the use-phase (driving only) is defined for a vehicle. The drive train of the vehicle comprises of the wheels, gearbox[6] and an internal combustion engine.

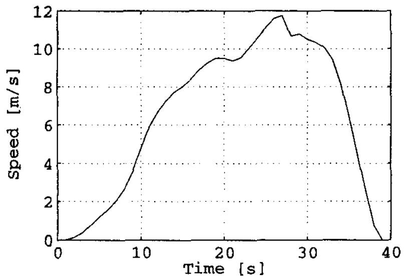
In **Fig. 6** the flowchart shows how the individual component models are connected, so that a calculated variable required for a specific component can be determined from the subsequent component. The models are represented by the boxes as was shown in **Fig. 5**. E.g. the models for the vehicle include the power required to overcome the forces from inertia, aerodynamic resistance and rolling resistance for a given speed, mass, etc.. The internal combustion engine can include models for mass as a function of maximum and average input torque and power and for the gearbox mass as a function of maximum and average input torque and speed, design life and number of gears. In the sizing routine the selection of different design parameters (e.g. number of gears, or lighter engine for same maximum and average input torque and power) will lead to an overall change in the vehicle mass and thus the use-phase simulation will show a change in energy required (fuel consumption).

The graphs in **Fig. 8** illustrate how for the use-phase of the vehicle the series data of vehicle speed vs. time **Fig. 8 (a)**, the type of gearbox modelled and which gear is selected for a given vehicle speed **Fig. 8 (b)** results in a specific engine speed **Fig. 8 (c)**.

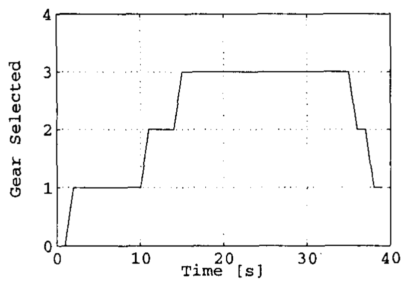
The total energy required by the combustion engine for the distance travelled and the type of engine is used to estimate emissions of the vehicle in terms of distance. Given the overall design life of the vehicle in kilometers allows a rough estimate of the use-phase emissions due to driving the vehicle.

Estimating the non-use phases' inventory can only be illustrated briefly here. They are determined from knowing the size of the components (by mass) and multiplying it with the parameterised LCI data for the different life cycle phases.

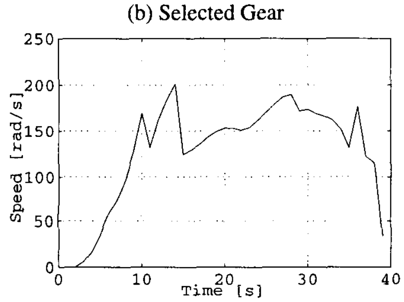
[6]The flowchart in **Fig. 6** depicts 2 gearboxes (each a single step), since the use of just one step would result in impractically large gear ratios. Here Gearbox 1 has just one gear, while Gearbox 2 comprises of 4 gears. In practice the single step would be included e.g. in the drive axis.



(a) Speed of Vehicle



(b) Selected Gear



(c) Rotational Speed of Gearbox 2 (driven end), engine speed

Figure 8. Sample Output

5. Conclusion

The representation of a complex product's inventory by means of the product's components' parameterised inventory and the mathematical representation of the components' behaviour relevant to the life cycle was illustrated. The LCA/LCC system module described together with various databases is implemented as a prototype software tool to estimate early during the design phase the relative importance of the design parameters on the life cycle.

It was further shown how the components' models are utilised in a flexible manner to represent the use-phase for the purpose of determining the size of the components for estimating the products use-phase inventory.

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