Data Validation in Life Cycle Assessment: A Review

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Abstract—**Uncertainties in Life Cycle Assessment (LCA) initiatives play a major role in influencing government policies and corporations strategic plans. Thus, it is important to ensure that the models of LCA initiatives are modeled such that they resemble emissions in the real world. In this paper, the authors have reviewed the uncertainty tools used in LCA initiatives. This is conducted such that LCA modelers understand the limitations and advantages associated with LCAs, and also identify areas where data can be refined. In an event where there is a shortage of data, conservative means can be used to approximate data to best model the effects of Global Warming in the real world are discussed.**

Index Terms—**Global Warming Potential, Greenhouse gases, Monte Carlo Simulation; Pedigree Matrix**

I. Introduction

A LIFE Cycle Assessment (LCA) of a system/product has become an integral part of products globally, and this stems from the need to preserve the plant for generations to come. As with a number of "new" endeavors in the sciences, knowledge in the discipline of Life Cycle Assessments is still developing, and one of the main points of contestation with Life Cycle Assessments is that studies are based on models, as empirical data is either absent or still being developed. This then begs the question of how reliable the quantitative data is in these studies.

In the current paper, the authors made use of a product with given quantitative data, and verify the information using a Pedigree Matrix to ascertain the level of confidence in the data, and then evaluated the overall level of confidence of the product (validation) by applying the Monte Carlo Simulation method [1] [2]. It should be noted that current software packages perform the aforementioned steps for the modeler of a Life Cycle Assessment. However, the need to perform the steps from first principles is imperative, as this can serve as a guide for prospective Life Cycle Assessment modelers in places where there is a scarcity of data to utilize, and thereafter validate.

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A. Problem Statement

A number of software packages commercially available to perform Life Cycle Assessments make use of information that might not necessarily cater for the modelers in their specific local regions. With this challenge, Life Cycle Assessment modelers are coerced into evaluating products using metrics that are not a true reflection of their respective regions, and to compound the problem even further, ISO clearly specifies that all Life Cycle Assessment initiatives need to be validated [3], and in the case of local regions using data that is not reflective of their particular regions, makes the data validation step futile.

B. Objectives

The paper is aimed at achieving the objectives stated below:

- Review the Pedigree Matrix,
- Review the Monte Carlo Simulation technique and its application in Life Cycle Assessment initiatives;
- Identify a product to be assessed to illustrate the fundamental principles of data validation in Life Cycle Assessments.

C. Methodology

The following methodology was followed in the development of the paper:

1) Global Warming potentials of a product analysis,
2) Pedigree Matrix for certain cases,
3) Monte Carlo Simulation modeling;
4) Review of aforementioned steps.

II. Literature Review

The ISO 14042 specifies that a compete Life Cycle Assessment initiative needs to have a data validation. Consequently, this implies that Life Cycle Assessments that make use of secondary data i.e. data that is not extracted from first hand sources need to indicate the margins of error in the data, or at least be transparent about their values, in order to avoid unethical behavior or raise perceptions of environmentally friendly product in comparison to competitors or misleading potentially affected stakeholders.

The current section considers the following topics that enable modeling the Life Cycle Assessment:

- Global Warming Potential,
- The Pedigree Matrix and its applications;
- Monte Carlo Simulation, and the applications thereof in Life Cycle Assessment initiatives.

A. *Global Warming Potential*

Global Warming Potential (GWP) stems from modeling the impact of greenhouse gases in the environment.

To appreciate the significates of Global Warming Potential and its meaning, there is a need to understand the greenhouse effect. The points below indicate the greenhouse effect phenomenon [4]:

1) Radiation from the sun penetrates the earth's atmosphere and reaches the surface of the earth,
2) About 50% of the radiation is absorbed by the earth while the balance is reflected,
3) In addition to the reflected radiation, the earth also gives off heat radiation of its own as well,
4) The reflected radiation goes back into space, however greenhouse gases (also consisting of anthropogenic processes) traps the radiation from escaping the earth's atmosphere;
5) The net result of increased heat radiation trapped in the earth's atmosphere is the ultimate increase in global temperatures.

From the aforementioned points, it is worth noting to wonder how the different greenhouse gases are compared, and how the different greenhouse gases contribute to the overall temperature increases in the globe. There are six categories of greenhouse gases as identified in the Kyoto Protocol and they are indicated as follows [5]:

1) Carbon Dioxide,
2) Methane,
3) Nitrous Oxide,
4) Sulphur Hexafluoride,
5) Hydrofluorocarbons;
6) Perfluorocarbons.

The aforementioned greenhouse gases all have different radiation retention lifespans, and they also differ chemically. It is due to these reasons that carbon dioxide was selected as a reference point to compare the different impact levels of greenhouse effects.

Global Warming Potential of a resource is thus a measure that compares the resource's impact in comparison to carbon dioxide. Consequently, carbon dioxide has a Global Warming Potential of 1, and all other greenhouse gases have Global Warming Potentials indexed from carbon dioxide's value of 1 as a reference. It should be noted that all global warming contributions of resources are measured in carbon dioxide equivalents, in order to standardize and compare results. Table 1 indicates the Global Warming Potentials of the six categorized greenhouse gases.

TABLE 1:
Global Warming Potential for 100-year Time Horizon [6]

Common Name	GWP
Carbon Dioxide	1
Methane	25
Nitrous Oxide	298
Sulphur Hexafluoride	22800
Hydrofluorocarbons(HFC-11)	4750
Perfluorocarbons(PFC-14)	7390

To quantify the greenhouse gases impact, it is important to know the quantities of greenhouse gases produced by the product, and then apply a conversion factors that can be used to translate the data in order to utilize the Global Warming Potential and ascertain the level of environmental impact of the product/resource. Equation 1 indicates the impact of a greenhouse gas calculation that has been explained:

Equation 1: Global Warming Impact of Greenhouse Gas [7]

$$i_{CO_{2eq}} = Q_{r,i} * EF * GWP \quad (1)$$

Where: $i_{co2\text{-}eq}$= Impact of greenhouse i, in global warming
$Q_{r,i}$=Quantity of resource r containing greenhouse gas i
EF=Correction Factor
GWP=Global Warming Potential

B. *Pedigree Matrix*

The Pedigree Matrix is a post-normal methodology that is, an attempt to characterize a methodology of probing scenarios that have a degree of uncertainty and are a function of the following:

- Uncertainty in facts,
- Data provided are questionable,
- There is an urgency in decision making;
- Stakes involved in the analysis of the data are high.

The Pedigree Matrix as applied in the paper is extracted from Ecoinvent database and has a matrix as indicated in Table 2.

TABLE 2:
Pedigree Matrix [8]

	1	2	3	4	5
Reliability	1	1.05	1.1	1.2	1.5
Completeness	1	1.02	1.05	1.1	1.2
Temporal Correlation	1	1.03	1.1	1.2	1.5
Geographical Correlation	1	1.01	1.02	1.02	1.1
Further Technological Correlation	1	1	1.2	1.5	2

Where:
Reliability = Verification of data based on measurements,
Completeness = Representative data from sufficient sample over a prolonged period to even out data oscillations,
Temporal Correlation = Is the data less than half a year to the Life Cycle Assessment Study?
Geographical Correlation = Data extracted from area under investigation;
Further Technological Correlation = Is the data from organisations, processes and materials under study?

It should be noted that the Pedigree Matrix is only as powerful as the conditions imposed upon it by the Life Cycle Assessment modeler. With that being said, the

Pedigree Matrix can be more beneficial in determining uncertainties, when expert judgement (from processes view point of a product) is utilised in the Life Cycle Assessment initiative. The total uncertainty using the Pedigree Matrix is calculated using Equation 2 as indicated below:

Equation 2 [9]:
Uncertainty Expressed as 95% Confidence Interval

$$SD_{g95} = e^{\sqrt{\sum_i [\ln(Ui)]^2}} \quad (2)$$

Where:
U_1=Uncertainty Factor of Precision,
U_2=Uncertainty Factor of Completeness,
U_3=Uncertainty Factor of Temporal Representativeness,
U_4=Uncertainty Factor of Geographical Representativeness,
U_5=Uncertainty Factor of Technological Representativeness;
U_b=Basic Uncertainty Factor.

It should be noted that basic uncertainty factors are proposed for different categories of activities or emissions.

C. *Monte Carlo Simulation*

The Monte Carlo Simulation fundamentally addresses the question of how the individual uncertainties impact to the entire model of one's Life Cycle Assessment initiative. This is addressed as follows. Given data with a degree of uncertainty, such as data modified after the utilisation of the Pedigree Matrix. One needs to ascertain how the input data of individual processes or resources ultimately impact the overall model, and this is referred to as sensitivity analysis in Life Cycle Assessments. The Monte Carlo method simulates random input parameters with the imposed level of confidence (as specified in the Pedigree Matrix for example), and thereafter the outputs of the entire model are observed. Thus allowing the modeler to make deductions regarding the varying input parameters, and identifying the drivers of the input parameters.

III. Global Warming Potential Product Review

The current section of the paper is split into three section as indicated below:

1) The product that is to be evaluated i.e. a litre of gasoline, and its global warming potential calculation,
2) The utilisation of the Pedigree Matrix on the product evaluated,
3) The application of Monte Carlo Simulation on the product evaluated;
4) Closing remarks.

A. *Warming Effect of a Litre of Gasoline*

Table 3 below indicates the properties of gasoline required to measure the warming effect of gasoline (petrol):

TABLE 3:
Gasoline (Petrol) Emission Factors [10]

Properties	**Values**
CO_2 Emission Factor	2.3051kg/l
CH_4 Emission Factor	0.0033 kg/l
N_2O Emission Factor	0.0059kg/l

Note that the values in Table 3 are already indicated in CO_2.e. This then implies that the values have already incorporated the greenhouse gases for the different Global Warming Potentials. Thus with reference to Equation 1 of the current paper the GWP term will fall off and the quantity of the resource (product) will also fall off assuming a 1 litre resource to be analysed.

Now that the product's warming effect have been indicated (Table 3), the following step would be to apply the Pedigree matrix to cater for circumstances where modelers need to adjust the data to cater for their particular local applications. The authors took on a conservative stand point in selecting the uncertainties (U values) in the Pedigree Matrix as indicated below. The decision was primarily driven by the logic that when region specific data is not available, a conservative approach can be employed and not just the norms implemented elsewhere, as those might be less conservative where the Life Cycle Assessment initiatives are being carried out.

TABLE 4:
Pedigree Matrix for Gasoline (Petrol)

	CO_2	**CH_4**	**N_2O**
Reliability	1	1	1
Completeness	1.2	1.2	1.2
Temporal Correlation	1.5	1.5	1.5
Geographical Correlation	1.1	1.1	1.1
Further Technological Correlation	2	2	2

The uncertainty of the data presented in Table 4 can then be expressed by making use of Equation 2 as indicated in Table 5:

Table 5:
Greenhouse Gases Uncertainty Levels

Greenhouse Gas	**Uncertainty%**
CO_2	2.29
CH_4	2.29
N_2O	2.29

With the uncertainties of the greenhouse gases established, what is left to do it to investigate how the data oscillates within the set interval given in Table 5, and to achieve this, the authors generated a Monte Carlo simulation with the imposed conditions as indicated in Figure 1:

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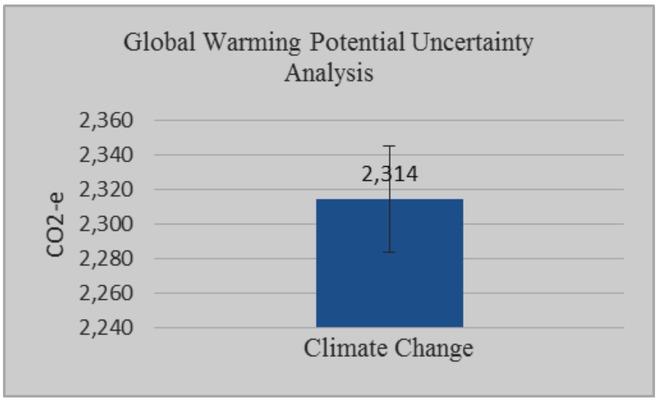

FIGURE 1:
Deviation from arithmetic mean of warming effect

In the Monte Carlo simulation conducted, a number of 5000 sample points were considered, and it can be seen that the total warming effect deviates from the mean value of 2.314 CO_2-e by an average 0.0307 CO_2-e which is about 1.33%.

IV. CONCLUSIONS

The paper was primarily intended to review the fundamental calculations utilized to analyse the sensitivity of Life Cycle Assessment Models. The product review evaluated can serve as a base for further studies, when it is required to verify the values obtained from Life Cycle Assessment packages, and even when it is required to generate own inventory which might either not be available on Life Cycle Assessment databases or the databases do not necessarily model the conditions of where the study is taking place

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