A PROJECT REPORT ON

LIFE CYCLE ASSESSMENT OF LMV ENGINES

Submitted in partial fulfilment of the requirements for the

Award of the degree of

BACHELOR OF TECHNOLOGY

In

MECHANICAL (AUTOMOBILE) ENGINEERING

Submitted by

AVINASH K V	:	**SCT16MA032**
GOUTHAM SUDHAKAR	:	**SCT16MA037**
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DEPARTMENT OF MECHANICAL ENGINEERING

SREE CHITRA THIRUNAL COLLEGE OF ENGINEERING,

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DECLARATION

We undersigned hereby declare that the project report “LIFE CYCLE ASSESSMENT OF LMV ENGINES”, submitted for partial fulfillment of the requirements for the award of degree of Bachelor of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by us under supervision of Dr. KAVILAL E G. This submission represents our ideas in our own words and where ideas or words of others have been included; we have adequately and accurately cited and referenced the original sources. We also declare that we have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. We understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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CERTIFICATE

Certified that project work entitled "**LIFE CYCLE ASSESSMENT OF LMV ENGINES**" is a bonafide work carried out in the seventh & eighth semester by "**AVINASH K V (SCT16MA032)**", **"GOUTHAM SUDHAKAR (SCT16MA037)", "R MAHESH KUMARAR (SCT16MA048)"**, "**ASWIN C (LSCT16MA065)"** in partial fulfilment for the award of Bachelor of Technology in "**MECHANICAL (AUTOMOBILE) ENGINEERING**" from Kerala Technological University during the academic year 2019-20 who carried out the project work under the guidance and no part of this work has been submitted earlier for the award of any degree.

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ABSTRACT

Vehicles have become the primary cause of greenhouse gas emissions. The amounts of emissions released from vehicles are creating havoc leading to the change in climatic conditions as well as living conditions in the world. An exhaustive technique used for estimating the energy consumption and environmental impacts associated with a vehicle is known as its life cycle assessment. This life cycle can be divided accordingly as fuel life cycle and engine life cycle. Pollutants from fuel life cycle is estimated using the GREET (Greenhouse gases regulated emissions and energy consumption in transportation) model. Engine life cycle emissions are calculated based on mass and type of material used for engine production, energy used for engine operation during its lifetime.

In most cases ICE vehicles are compared with Electric vehicles due to their less pollution and feasibility, but when it comes to manufacturing and production, their cost is way higher. Thus conventional energy sources need to be utilized upto a certain extent until the technical developments reaches the best.

In our project we have considered the average emission values of a Diesel LMV Engine that was run for about 30 years. The values were taken from the GREET manual and the corresponding emissions were calculated based on equations referred from different journals. An open source software known as openLCA was used to analyze the environmental impacts associated with it.

From the results obtained from LCA we can develop methods to reduce the environmental impact of the process or phase that has a high impact by modifying the technology or addressing the material inputs of the engine.

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ABBREVIATIONS

LCA	LIFE CYCLE ASSESSMENT
LMV	LIGHT MOTOR VEHICLE
ICE	INTERNAL COMBUSTION ENGINE
LCI	LIFE CYCLE INVENTORY
LCIA	LIFE CYCLE IMPACT ASSESSMENT
ISO	INTERNATIONAL ORGANISATION FOR STANDARDIZATION
EPA	UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
CO2	CARBON DIOXIDE
VOC	VOLATILE ORGANIC COMPOUNDS
PM	PARTICULATE MATTER
NOX	NITROGEN OXIDES
GREET	GREENHOUSE GASES REGULATED EMISSIONS AND ENERGY USAGE IN TRANSPORTATION

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The transportation sector is one of the major contributors for global warming and greenhouse gas emissions. In the last 10 years, the global CO_2 emission increased by 13%, with 25% of the rise coming from transportation sector. Furthermore, by 2050, the global CO_2 emission is still expected to extend by 30%-50%. The proportion of the total CO_2 emissions by transportation sector is highest in China (30.98%) followed by Germany (19.9%) and United States (7.86%) and this proportion varies across different countries.

Transport sector contributes to about 1/3 rd of the overall energy consumption in the world. Also, 25% of the overall CO_2 emission is from the transport sector. Internal combustion engines (ICE) vehicles are the main power type of vehicles and contribute most of the total CO_2 emission in the transport sector. In the automobile industry, the IC engines are now at mature stage. Therefore, the assessment of environmental impacts of IC engines is of much relevance. However, in order to assess the environmental impacts associated with a vehicle in its life time, a comprehensive approach has to be considered. This approach is called life cycle assessment (LCA), which includes all the steps required, to manufacture a vehicle and to operate and maintain the vehicle throughout its life time including disposal and recycling at the end of its life cycle. Vehicle life cycle includes vehicle material production, assembly of the vehicle, distribution, operation, maintenance, and disposal.

Life cycle assessment is a technique to assess the environmental impacts associated with all stages of life cycle of any product/process. The LCA study contains four iterative steps. They are goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results. LCA helps in attaining sustainability.

1.2 INTRODUCTION TO LCA

Life cycle assessment (LCA / life cycle analysis / cradle-to-grave) analysis is a methodology for assessing the environmental impacts related to all the stages of the life-cycle of a commercial product, process, or service. For instance, in the case of a manufactured product, environmental impacts are assessed from raw material extraction and processing (cradle), through the product's manufacture, distribution and use, to the recycling or final disposal of the materials composing it (grave).

A LCA study involves an intensive inventory of the energy and materials that are required across the industry value chain of the product, process or service, and calculates the corresponding emissions to the environment. LCA thus assesses the cumulative potential environmental impacts. The aim of LCA is to document and improve the overall environmental profile of the product.

Widely recognized procedures for conducting LCAs are included within the 14000 series of environmental management standards of the International Organisation for Standardisation (ISO), especially, in ISO 14040 and ISO 14044.

1.3 DEFINITION OF LCA

As stated by the National Risk Management Research Laboratory of the EPA, LCA is a technique to assess the environmental aspects and potential impacts related to a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases.
- Evaluating the potential environmental impacts associated with identified inputs and releases.
- Interpreting the results to help you make a more informed decision.

Hence, it is a way to assess environmental impacts related to all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Designers use this process to assist critique their products.

The goal of LCA is to match the complete range of environmental effects assignable to products and services by quantifying all inputs and outputs of material flows and assessing how these material flows affect the environment. This information is employed to enhance processes, support policy and provide a sound basis for informed decisions.

LCA also has major roles in environmental impact assessment, integrated waste management and pollution studies.

The term life-cycle refers to the concept that an honest assessment requires the assessment of raw-material production, manufacturing, distribution, use and disposal including all intervening transportation steps necessary or caused by the product's existence.

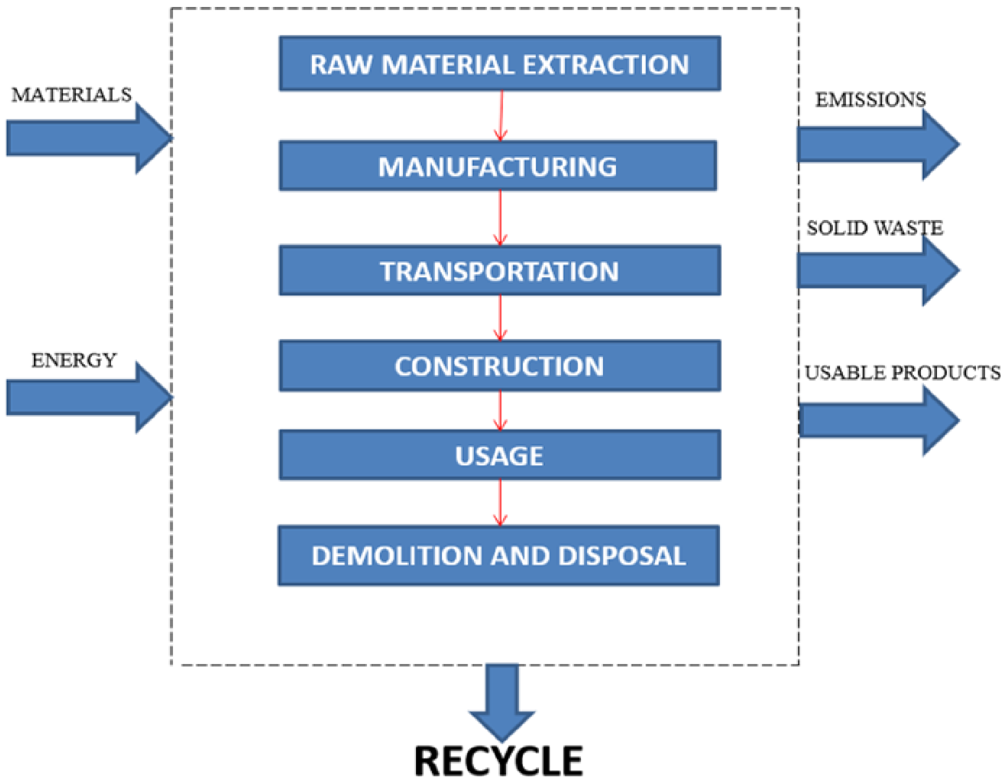

Fig. 1.1: Stages in life cycle of a product

1.4 MAIN ISO PHASES OF LCA

According to standards in the ISO 14040 and 14044, LCA is carried out in four distinct phases, as illustrated in the figure. The phases are often interdependent, that is the results of one phase will influence how the other phases are completed.

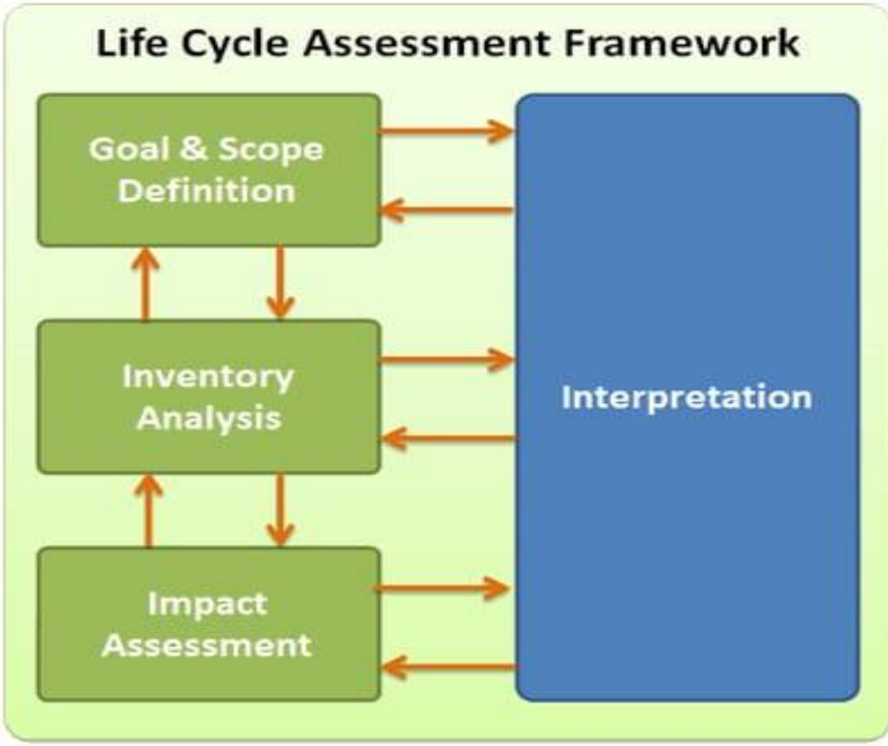

Fig. 1.2: LCA Framework

1.4.1 GOAL AND SCOPE DEFINITION

An LCA starts with a particular statement of the goal and scope of the study, which sets out the context of the study and explains how and to whom the results are to be communicated. This is a key step and the ISO standards require that the goal and scope of an LCA should be clearly defined and consistent with the intended application. The goal and scope document, therefore, includes the technical details that guide subsequent work:

- **The functional unit**, which defines precisely what is being studied, quantifies the service delivered by the system, provides a reference to which the inputs and outputs can be related, and provides a basis for comparing / analyzing alternative goods or services.
- **The system boundaries**, which delimit which processes should be included in the analysis of a system, including whether the system produces any co-products that must be accounted for by system expansion or allocation.
- **Any assumptions and limitations**;

- **Data quality requirements**, which specify the kinds of data that will be included and what restrictions (date range, completeness, county or region of study, etc.) will be applied.
- **The allocation methods**, which are used to partition an environmental load of a process when several products or functions share the same process. Allocation is usually addressed in one among three ways: system expansion, substitution, and partition. Choice of allocation method for co-products can have a significant impact on the results of an LCA.
- **The impact categories**, which might include such categories as human toxicity, smog, global warming, and eutrophication.

1.4.2 INVENTORY ANALYSIS

Life Cycle Inventory (LCI) analysis involves the creation of an inventory of flows from and to the nature for a product system. Inventory flows include inputs of water, energy, and raw materials, and releases to air, land, and water, etc. To develop the inventory, a flow model of the technical system is made using data on inputs and outputs. The flow model is usually illustrated with a flow chart that includes the activities that are going to be assessed and it gives a clear picture of the technical system boundaries. The input and output data needed for the development of the model are collected for all activities within the system boundary, including from the supply chain.

The data must be associated with the functional unit defined in the goal and scope definition. Data are often presented in tables and some interpretations are often made already at this stage. The results of the inventory is an LCI which provides information about all the inputs and outputs within the sort of elementary flow to and from the environment from all the unit processes involved in the study.

Inventory flows can number in the hundreds counting on the system boundary. For product LCAs at either the generic or brand-specific level, the data is typically collected through survey questionnaires. At an industry level, care has got to be taken to make sure that questionnaires are completed by a representative sample of producers, leaning toward neither the best nor the worst, and fully representing any regional differences due to energy use, material sourcing or other factors. The questionnaires should cover the complete range of inputs and outputs, typically aiming to account for 99% of the mass of a product, 99% of the energy utilized in its production and any environmentally sensitive flows, even if they fall within the 1% level of the inputs.

The one undertaking the LCA must turn to secondary sources if it does not already have that data from its own previous studies. National databases or data sets that accompany LCA-practitioner tools, or that can be readily accessed, are the usual sources for that information. Care must then be taken to make sure that the secondary data source properly reflects regional or national conditions.

Life cycle inventory methods include process LCAs, economic input–output LCA (EIOLCA), and hybrid approaches.

1.4.3 IMPACT ASSESSMENT

Inventory analysis is followed by a life-cycle impact assessment (LCIA). This phase of LCA is aimed toward evaluating the significance of potential environmental impacts based on the life-cycle impact flow results. Classical LCIAs consist of the following mandatory elements:

- **selection** of impact categories, category indicators, and characterization models;
- the **classification** stage, where the inventory parameters are sorted and assigned to specific impact categories; and
- impact **measurement**, where the categorized LCI flows are characterized, using one of many possible LCIA methodologies, into common equivalence units that are then summed to provide an overall impact category total.

In many LCAs, characterization concludes the LCIA analysis, it is the last compulsory stage as per to ISO 14044. However, additionally to the mandatory LCIA steps, other optional LCIA elements like normalization, grouping, and weighting could also be conducted based on the goal and scope of the LCA study. In normalization, the results of the impact categories from the study are usually compared with the total impacts within the region of interest. For example, the United States Grouping consists of sorting and possibly ranking the impact categories. During weighting, the various environmental impacts are weighted relative to each other so that they can then be summed to get a single number for the total environmental impact. ISO 14044 generally advises against weighting, stating that weighting, shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the general public. This advice is usually ignored, leading to comparisons which will reflect a high degree of subjectivity as a result of weighting.

Life cycle impacts also can be categorized under the several phases of the development, production, use, and disposal of a product. Broadly speaking, these impacts are often divided into first impacts, use impacts, and end of life impacts. First impacts include extraction of raw materials, manufacturing, transportation of the merchandise to a market or site, construction/installation, and the beginning of the use or occupancy. Use impacts include physical impacts of operating the product or facility (such as energy, water, etc.), and any maintenance, renovation, or repairs that are required to continue to use the product or facility. End of life impacts include demolition and processing of waste or recyclable materials.

1.4.4 INTERPRETATION OF RESULTS

Life-cycle interpretation is a systematic technique to identify (spot), quantify, check, and evaluate information from the results of the life cycle inventory and / or the life cycle impact assessment. The results from the inventory analysis and impact assessment are summarised during the life cycle interpretation phase. The outcome of the interpretation phase is a set of conclusions and proposals for the study. According to ISO 14040, the interpretation should include:

- identification of significant issues based on the results of the LCI and LCIA phases of an LCA;
- evaluation of the study considering completeness, sensitivity and consistency checks; and
- conclusions, limitations and recommendations.

A key purpose of performing life cycle interpretation is to work out the extent of confidence within the ultimate results and communicate them in a fair, complete, and accurate manner. Interpreting the results of an LCA is not a simple process. Interpretation begins with understanding the accuracy of the results, and ensuring that they meet the goal of the study. This is accomplished by identifying the info (data) elements that contribute significantly to each impact category, evaluating the sensitivity of these significant data elements, assessing the completeness and consistency of the study, and drawing conclusions and recommendations or proposals based on a clear understanding of how the LCA was conducted and the results were developed.

Specifically, the goal of the LCA interpretation phase is to identify the alternative that has the least cradle-to-grave environmental negative impact on land, sea, and air resources.

1.5 DATA ANALYSIS IN LCA

A life cycle analysis is merely as accurate and valid as is its basis set of data. There are two fundamental sorts of LCA data: unit process data, and environmental input-output (EIO) data. Unit process data are derived from direct surveys of companies or plants producing the product (merchandise) of interest, administered at a unit process level defined by the system boundaries for the study. EIO datas are based on national economic input-output data.

Data validity is a concern for life cycle analyses. If LCA conclusions are to be valid, data utilized in the LCA inventory must accurate and valid. Moreover, when comparing a pair of LCAs for various products, processes, or services, it is crucial that data of equivalent quality are available for the pair being compared. That means that a product which has a much higher availability of accurate and valid data cannot be justly compared to another product which has lower availability of such data.

Due to globalization and the pace of research and development, new materials and manufacturing methods are continually being introduced to the market, making it both important and difficult to identify and apply up-to-date information. Thus, creating a need for rapid, up to date data collection.

As mentioned above, the inventory in the LCA usually considers a number of stages including: materials extraction, processing and manufacturing, product use, and product disposal. If the most environmentally harmful of these stages can be determined, then impact on the environment can be efficiently reduced by focusing on making changes for that specific phase. For example, the most energy-intensive stage in the LCA of an aircraft or automobile product is during its usage, as a result of fuel consumption during the product lifetime. An effective ways to increase fuel efficiency is to decrease the vehicle weight; hence, aircraft and automobile manufacturers can decrease the environmental impact through replacement of heavier materials with lighter ones, all specifications and other costs being equal.

Data sources utilized in LCAs are typically large databases. It is not appropriate to compare two options if different data sources have been used to source the data.

Common data sources include:

- ecoinvent
- soca
- EuGeos' 15804-IA
- NEEDS
- PSILCA
- ESU World Food
- GaBi
- ELCD
- LC-Inventories.ch
- Social Hotspots
- ProBas
- Bioenergiedat
- Agribalyse
- USDA
- Ökobaudat
- Agri-footprint
- Comprehensive Environmental Data Archive (CEDA)

Calculations for impact can then be done by hand, but it is more usual to do the process by using software. This can range from a simple spreadsheet, where the user enters the data manually to a fully automated program, where the user is not aware of the source data.

1.6 VARIANTS OF LCA

1.6.1 CRADLE-TO-GRAVE

Cradle-to-grave is the full Life Cycle Assessment, i.e., from resource extraction (cradle) to use phase and disposal phase (grave). All inputs and outputs are considered for all the phases of the life cycle.

1.6.2 CRADLE-TO-GATE

Cradle-to-gate is a partial product life cycle, i.e., from resource extraction (cradle) to the factory gate (i.e., before it is transported to the consumer). The use phase and disposal phase of the product are not considered in this case. One of the many uses of the cradle-to-gate approach compiles the life cycle inventory (LCI) using cradle-to-gate. This allows the LCA to collect all of the impacts leading up to resources being purchased by the facility. They can then add the steps involved in their transport to plant and manufacture process to more easily produce their own cradle-to-gate values for their products.

1.6.3 CRADLE-TO-CRADLE OR CLOSED LOOP PRODUCTION

Cradle-to-cradle is a specific kind / type of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process. It is a method with an objective to minimize the environmental impact of the products by employing sustainable production, operation, and disposal practices and aims to incorporate social responsibility into product development. From the recycling process originate new, identical products (e.g., asphalt pavement from discarded asphalt pavement, glass bottles from collected glass bottles), or different products (e.g., glass wool insulation from collected glass bottles).

Allocation of burden for products in open loop production systems presents considerable challenges for LCA. Various methods, such as the avoided burden approach have been proposed to deal with the issues involved.

1.6.4 GATE-TO-GATE

Gate-to-gate is a partial LCA looking at only one value-added process within the entire production chain. Gate-to-gate modules can also later be linked in their appropriate production chain to form a complete cradle-to-gate evaluation.

1.6.5 WELL-TO-WHEEL

Well-to-wheel is the specific LCA used for transport fuels and vehicles. The analysis is often broken down into stages like "well-to-station", or "well-to-tank", and "station-to-wheel" or "tank-to-wheel", or "plug-to-wheel". The first stage, which includes the feedstock or fuel production and processing and fuel delivery or energy transmission, and is called the "upstream" stage, while the stage that deals with vehicle operation itself is usually called the "downstream" stage. The wheel-to-wheel analysis is commonly used to assess the total energy consumption, or the energy conversion efficiency and the emission impact of marine vessels, aircraft and automobiles, including their carbon footprint, and the fuels used in each of these transport modes. WTW analysis is useful for reflecting the various efficiencies and emissions of energy technologies and fuels at both the upstream and downstream stages, giving a more complete picture of real emissions.

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model was developed to evaluate the impacts of latest fuels and vehicle technologies. The model evaluates the impacts of fuel use employing a well-to-wheel evaluation while a traditional cradle-to-grave approach is employed to determine the impacts from the vehicle itself. The model reports energy use, greenhouse gas emissions, and six additional pollutants: volatile organic compounds (VOCs), carbon monoxide(CO), nitrogen oxide (NOx), particulate matter with size smaller than 10 micrometre (PM10), particulate matter with size smaller than 2.5 micrometre (PM2.5), and sulphur oxides (SOx). Quantitative values of greenhouse emissions calculated with the WTW or with the LCA method can differ, since the LCA is considering more emission sources.

CHAPTER 2

LITERATURE SURVEY

1. A journal paper by Dawei Wang et al on **"Life cycle analysis of internal combustion engine, electric and fuel cell vehicles for China"** compares the energy and carbon emission values of an ICE vehicle with an EV. It considers the production, assembly and disposal phases of an ICE vehicle and makes a comparison with EV emissions by different metals in both cases.
2. A journal paper by Francesco Del Pero et al on **"Life cycle assessment in the automotive sector: a comparative case study of ICE and electric car"** shows the life cycle of a car subdivided into different phases such as production, usage and end of life. The impacts due to emissions such as GHG are discussed and strategical methods are chosen.
3. A journal paper by Gowri et al on **'Life cycle assessment of conventional and electric vehicles'** points on the impact of life cycle CO2 emissions of ICE vehicles and electric vehicles. Here electric vehicles are the primary source of energy consumption and their pollutants vary accordingly by the processes carried out for their manufacturing. The life cycle is divided into two parts-fuel life cycle and vehicle life cycle and comparisons are made.
4. A journal paper by Mrozik and Danilecki on **'Environmental assessment of the production process of internal combustion engines'** shows the changes in the material composition in engines of Volkswagen Golf passenger car in 30 years. The changes in energy consumption and CO_2 emissions are displayed using LCA. The amount of steel, cast steel and cast iron are needed to be reduced so that environmental burden can be reduced. The recycling of other materials can significantly reduce the environmental burden.
5. A journal paper by Dorota and Piotr on **'Comparative life cycle assessment of chosen passenger cars with internal combustion engines'** shows the comparative environmental life cycle assessment of petrol and diesel fuelled vehicles. Carbon footprints (CO2, CH4, CO etc.) and respiratory inorganics (sulphur, particulates) are

the major emissions released from IC engines. The results show the carbon footprint and respiratory inorganics emissions of diesel engine are low and high respectively. Thus, by the use of alternative fuels can lower the emissions mentioned above.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

GOAL	• Life cycle assessment of Diesel engine
SCOPE	• Using LCA, it is possible to identify the processes generating environmental burden and modifications to reduce them. • By only knowing the average emission and enrgy values of diesel engine, we can find environmental impacts
LCIA	• Production • Usage • End of life • Energy requirements and emission regulations in this stage decide the overall impact on environment.
RESULTS	Reporting the results obtained from LCIA

Table 3.1: Methodology

As mentioned above, LCA is an environmental accounting methodology which allows identifying, quantifying and assessing the impacts involved by the entire life cycle of a product/process based on the inventory of all environmentally relevant flows (i.e., emissions, energy, resources, waste).

3.2 GOAL & SCOPE DEFINITION

As per our project, the goal is to assess the environmental impacts caused by the operation of a particular diesel engine and the changes that occurs due to its operation. The functional unit used in this study is the 30 year (1990-2020) average emissions released during its period. By identifying the overall pollutants produced as a result of this particular diesel engine, it is possible to identify ways to reduce them by choosing alternatives such as change in material composition, change in engine design, change in fuel consumption etc. so that its life cycle tends to last for a particular age.

3.3 LIFE CYCLE INVENTORY ANALYSIS

This stage consists of collecting and processing of all the necessary data to analyse the system under study. These include changes that occur during engine life. The inventory mainly depends on primary data which is obtained from a detailed information report and secondary data for analysing the results for better understanding of the work done. For this inventory is divided into different stages such as production, usage, end of life.

Production phase covers the entire construction process, from raw material extraction to the production manufacturing. The energy consumption and emission during this phase helps us to determine the different impacts categories that make the global climate vulnerable to the existing surroundings. For this purpose, we have taken a formula from journal for identifying the overall emission produced, based on different material compositions.

Usage phase consist of the energy production and emission during the operation of the engine. This varies according to the engine speed, engine capacity, engine size, fuel consumption etc. In our case, almost 70% emissions are more of carbon footprints, so by applying the values for diesel fuel, we were able to calculate the emission factors of different pollutants. This was achieved by utilising some important formulas from different journals.

End-of-life (EoL) modelling in life cycle assessment has already been broadly discussed within several studies. However, no concurrence has been achieved on how to model recycling in LCA, even though several approaches have been developed. EoL scenarios are mainly recycling, incineration and landfill.

3.4 EQUATIONS FOR INVENTORY ANALYSIS

3.4.1 PRODUCTION PHASE

- Material Production Carbon Emission (Cm) is given by:

$$Cm = \propto m * Mm * \beta m * (10^{-6}) \quad [5]$$

- Material Production Energy Consumption is given by:

$$Em = \propto m * Mm \quad [5]$$

Where,

Cm = Material production carbon emission [kg]

Em = Material production energy consumption [kJ]

$\propto m$ = Energy consumption factor [kJ/kg]

Mm = Mass of the material [kg]

βm = Material production carbon emission factor [kg/GJ]

It is given by:

$$\beta m = (Pt\beta t + Pe\beta e) \quad [5]$$

Where ‘Pt’ and ‘Pe’ are the percentages of the thermal energy and electrical energy needed needed in material production respectively.

3.4.2 USAGE PHASE

- Emission of pollutant ‘i’ during usage phase is given by:

$$EMi = EFi * EC \quad [1]$$

Where,

EMi = Combustion emissions of pollutant i [g/J]

EFi = Emission factor of pollutant i [g/J]

EC = Inverse efficiency ratio for consumption of fuel

- Emission factor for CO_2 is given by:

$$EF_{CO2} = [(\rho/LHV) * Cratio - (VOC*0.85 + CO*0.43 + CH_4*0.75)] * (44/12) \quad [1]$$

Where,

EF_{CO2} = Emission factor for CO_2 [g/J]

ρ = Density of fuel [g/l]

LHV = Low heating value of fuel [J/l]

$Cratio$ = Carbon ratio of fuel

VOC = VOC emission factor [g/J]

CO = CO emission factor [g/J]

CH_4 = CH_4 emission factor [g/J]

0.85 = Carbon ratio of VOC

0.43 = Carbon ratio of CO

0.75 = Carbon ratio of CH_4

44 = Molecular weight of CO_2

12 = Molecular weight of elemental carbon

3.4.3 END OF LIFE

- Energy consumption on disposal phase is given by:

$$E_{dp} = \propto_{dp} * M \qquad [5]$$

Where,

E_{dp} = Energy consumption on disposal phase

$\propto_{dp}$ = Energy consumption factor

M = the required mass

3.5 CALCULATIONS

In our project, we are considering an LMV Diesel Engine for doing the life cycle assessment. By substituting the data associated with the diesel engine in the above equations, we get the inventory data for doing the life cycle assessment.

The data associated with the diesel engine and the diesel fuel is as follows:

- Weight of the selected Diesel engine, M = 140kg
- Calorific Value of Diesel Fuel = 45.5*10^3 kJ/kg
- Density of Diesel = 0.85
- Carbon ratio of Diesel= 0.865
- LHV of diesel = 0.036 J/l

The calculations are as follows:

3.5.1 PRODUCTION PHASE

Carbon emission in production phase is given by;

$$C_m = \propto_m * M_m * \beta_m * (10^{-6})$$

The diesel engine is mainly composed of Steel and Aluminium. Therefore, the carbon emissions of Aluminium and Steel are to be calculated.

- **Steel**
  - Weight of the selected Diesel engine, M =140kg
  - Average energy consumption factor, $\propto$ =19750 kJ/kg
  - Percentage of thermal energy needed for production, Pt = 85%
  - Thermal carbon emission factor, βt =23.3 kg/GJ
  - Percentage of electrical energy needed for production Pe = 15%
  - Electrical carbon emission factor, βe =54 kg/GJ

  Total carbon emission factor for steel is given by:

  - $\beta st = (Pt\beta t + Pe\beta e)$

    $= 0.85*23.3 + 0.15*54$

    $= 27.905$ kg/GJ

  Hence, total carbon emission associated with steel,

  - Cst = 19750* 140* 27.905* 10^-6

    = 77 kg

- **Aluminium**
  - Percentage of thermal energy needed for production, Pt = 25%
  - Thermal carbon emission factor, βt =20.9kg/GJ,
  - Percentage of electrical energy needed for production, Pe = 75%
  - Electrical carbon emission factor, βe = 54kg/GJ

  Total carbon emission factor for aluminium is given by:

  - $\beta Al = (Pt\beta t + Pe\beta e)$

    $= 0.25*20.9 + 0.75*54$

    $= 45.725$ kg/GJ

  - Hence, total carbon emission associated with aluminium,

  - CAl = 19750* 140* 45.725* 10^-6

    = 126kg

- Material production energy consumption,

  $Em = \propto m * Mm$

= 19750* 140

= 2.765* 10^6 kJ

3.5.2 USAGE PHASE

For doing calculations associated with the usage phase, an assumption is required. **Assumption**: 1 hour running at an average speed of 45km/hr requires 45500 J of energy per gram fuel consumption.

From this assumption, we can interpret that the car requires approximately 1.5 minutes to cover 1 km.

Calorific value of fuel = 45.5*10^3 kJ/kg = 45.5*10^3 J/g. i.e., 1 kg of fuel requires 45500 J of energy.

To standardize we have to convert to m/s:

- [(45.5*10^3*1.5)/60] * (5/18) = 315.97

All the data's are taken from the GREET manual as primary data collection was difficult. The emission factors given in the GREET manual is in g/mile. But in the equation, the emission factors are in g/J. Therefore, unit conversion must be applied before substituting in the equation. These are as follows:

- VOC factor, VOC = 0.0716 / (315.97*1.6)

  = 0.0001416 g/J
- EF_{CO}, CO = 2.7137/ (315.97*1.6)

  = 0.00536 g/J
- EF_{CH_4}, CH_4 = 0.092/ (315.97*1.6)

  = 0.00018 g/J
- EF_{NO_2} = 0.2311/ (315.97*1.6)

  = 0.000457 g/J
- EF_{PM} = 0.0050/ (315.97*1.6)

  = 9.89*10^-6 g/J
- EF_{N20} = 0.0007/ (315.97*1.6)

  = 1.38*10^-6 g/J

Model Year	VOC, exhaust	VOC, evaporation	CO	NO_x	SO_2	PM_{10}, exhaust	PM_{10}, OC	PM_{10}, BC	PM_{10}, Sulfate
2001	0.1610		0.3016	0.9182	0.0446	0.1261	0.0447	0.0783	0.00320
2002	0.1604		0.3009	0.9162	0.0381	0.1254	0.0445	0.0782	0.00274
2003	0.1600		0.3004	2.6403	0.0314	0.1247	0.0443	0.0781	0.00225
2004	0.1598		0.3001	2.6393	0.0243	0.0075	0.0046	0.0012	0.00174
2005	0.1597		0.3000	2.6390	0.0169	0.0070	0.0046	0.0012	0.00121
2006	0.0627		0.3954	0.4509	0.0092	0.0064	0.0046	0.0012	0.00066
2007	0.0312		0.3953	0.4508	0.0058	0.0062	0.0046	0.0012	0.00042
2008	0.0308		0.3940	0.4504	0.0043	0.0051	0.0038	0.0010	0.00031
2009	0.0307		0.3939	0.4502	0.0037	0.0051	0.0038	0.0010	0.00027
2010	0.0750		2.7274	0.2339	0.0031	0.0051	0.0038	0.0010	0.00023
2011	0.0751		2.7289	0.2339	0.0029	0.0051	0.0038	0.0010	0.00021
2012	0.0737		2.7309	0.2339	0.0024	0.0050	0.0038	0.0010	0.00017
2013	0.0735		2.7329	0.2339	0.0023	0.0050	0.0038	0.0010	0.00017
2014	0.0733		2.7345	0.2338	0.0022	0.0050	0.0038	0.0010	0.00016
2015	0.0730		2.7357	0.2336	0.0021	0.0050	0.0039	0.0010	0.00015
2016	0.0726		2.7362	0.2333	0.0020	0.0050	0.0039	0.0010	0.00014
2017	0.0724		2.7360	0.2329	0.0020	0.0050	0.0039	0.0010	0.00014
2018	0.0722		2.7352	0.2324	0.0020	0.0050	0.0039	0.0010	0.00014
2019	0.0719		2.7337	0.2318	0.0020	0.0050	0.0039	0.0010	0.00014
2020	0.0716		2.7317	0.2311	0.0020	0.0050	0.0039	0.0010	0.00014

Table 3.2: Lifetime mileage-weighted average air pollutant emission factors (g/mile) for diesel passenger cars for model years 2001–2020

Model Year	PM_{10}, TBW	$PM_{2.5}$, exhaust	$PM_{2.5}$, OC	$PM_{2.5}$, BC	$PM_{2.5}$, Sulfate	$PM_{2.5}$, TBW	CH_4	N_2O
2001	0.0180	0.1224	0.0433	0.0759	0.00312	0.0046	0.0006	0.0007
2002	0.0180	0.1217	0.0431	0.0759	0.00267	0.0046	0.0006	0.0007
2003	0.0180	0.1210	0.0430	0.0758	0.00219	0.0046	0.0006	0.0007
2004	0.0180	0.0073	0.0044	0.0012	0.00170	0.0046	0.0006	0.0007
2005	0.0180	0.0068	0.0044	0.0012	0.00118	0.0046	0.0006	0.0007
2006	0.0180	0.0062	0.0044	0.0012	0.00065	0.0046	0.0033	0.0007
2007	0.0180	0.0060	0.0044	0.0012	0.00041	0.0046	0.0340	0.0007
2008	0.0180	0.0050	0.0037	0.0010	0.00030	0.0046	0.0333	0.0007
2009	0.0180	0.0049	0.0037	0.0010	0.00026	0.0046	0.0333	0.0007
2010	0.0180	0.0049	0.0037	0.0010	0.00022	0.0046	0.0938	0.0007
2011	0.0180	0.0049	0.0037	0.0010	0.00021	0.0046	0.0938	0.0007
2012	0.0180	0.0049	0.0037	0.0010	0.00017	0.0046	0.0938	0.0007
2013	0.0180	0.0049	0.0037	0.0010	0.00016	0.0046	0.0937	0.0007
2014	0.0180	0.0049	0.0037	0.0010	0.00016	0.0046	0.0936	0.0007
2015	0.0180	0.0049	0.0037	0.0010	0.00015	0.0046	0.0935	0.0007
2016	0.0180	0.0049	0.0037	0.0010	0.00014	0.0046	0.0933	0.0007
2017	0.0180	0.0049	0.0037	0.0010	0.00014	0.0046	0.0930	0.0007
2018	0.0180	0.0049	0.0037	0.0010	0.00014	0.0046	0.0927	0.0007
2019	0.0180	0.0049	0.0037	0.0010	0.00014	0.0046	0.0924	0.0007
2020	0.0180	0.0049	0.0037	0.0010	0.00014	0.0046	0.0920	0.0007

Table 3.3: Lifetime mileage-weighted average air pollutant emission factors (g/mile) for diesel passenger cars for model years 2001–2020

- CO_2 emission factor,

$$EF_{CO2} = [\rho / LHV * Cratio - (VOC * 0.85 + CO * 0.43 + CH4 * 0.75)] * (44 \div 12)$$

$= [0.85/0.036 * 0.865 - (0.0001416 * 0.85 + 0.00536 * 0.43 + 0.0000505 * 0.75)] * (44 \div 12)$

$EF_{CO_2} = 74.8667$ g/J

- ❖ Inverse efficiency ratio is the inverse of fuel efficiency of the engine.
- ❖ Fuel Efficiency of diesel engine is approximately 30%
- ❖ So, inverse fuel efficiency,

$EC = 1/.3 = 3.33$

- ❖ $EM_i = EF_i * EC$
- o Emission of CO_2,

$EM_{CO_2} = 74.8667 * 3.33$

$= 249.306$ g/J

- o NOx emission,

$EM_{NOx} = (0.000457 + 1.38*10^{-6})* 3.33$

$= 0.001526$ g/J

- o Particulate matter emission,

$EM_{PM} = 9.89 * 10^{-6} * 3.33$

$= 3.29 *10^{-5}$ g/J

- o Total Emission,

$EM_{Total} = EM_{CO_2} + EM_{NOx} + EM_{PM}$

$= 249.306 + 0.001526 + 3.29*10^{-5}$

$= 249.30756$ g/J

3.5.3 END OF LIFE

- ➢ Energy consumption factor, $\propto_{dp} = 370$ KJ/kg
- o Energy consumption on disposal phase,

$E_{dp} = \propto_{dp} * M$

$= 370 * 140$

$= 5.18 * 10^4$ KJ

Carbon emission value in end of life is very small. Hence, it is neglected.

CHAPTER 4

EXPERIMENTS

4.1 openLCA SOFTWARE

openLCA is a source and free software for sustainability and life cycle assessment, with the following features:

- Open source software.
- Fast and reliable calculation of your sustainability assessment / life cycle assessment.
- Very detailed insights into calculation and analysis results.
- Identification of main drivers throughout the life cycle by process, flow or impact category, visualise results and locate them on map.
- Best in class import and export categories.
- User friendly, user interface in a variety of languages; advanced and efficient repository and collaboration feature (under development).
- Available for windows, mac, linux and several other platforms.

openLCA offers the largest collection of data sets and database globally for LCA software, some for purchase and most for free; where almost 100,000 databases are available. A website named openLCA nexus was created in 2012 for accessing free/purchasable databases. These are aligned as much as possible with the software. Initially, the main application of openLCA was environmental life cycle assessment, and was later extended to enable economic life cycle assessment models, especially in a combination with LCA, in the form of life cycle costing.

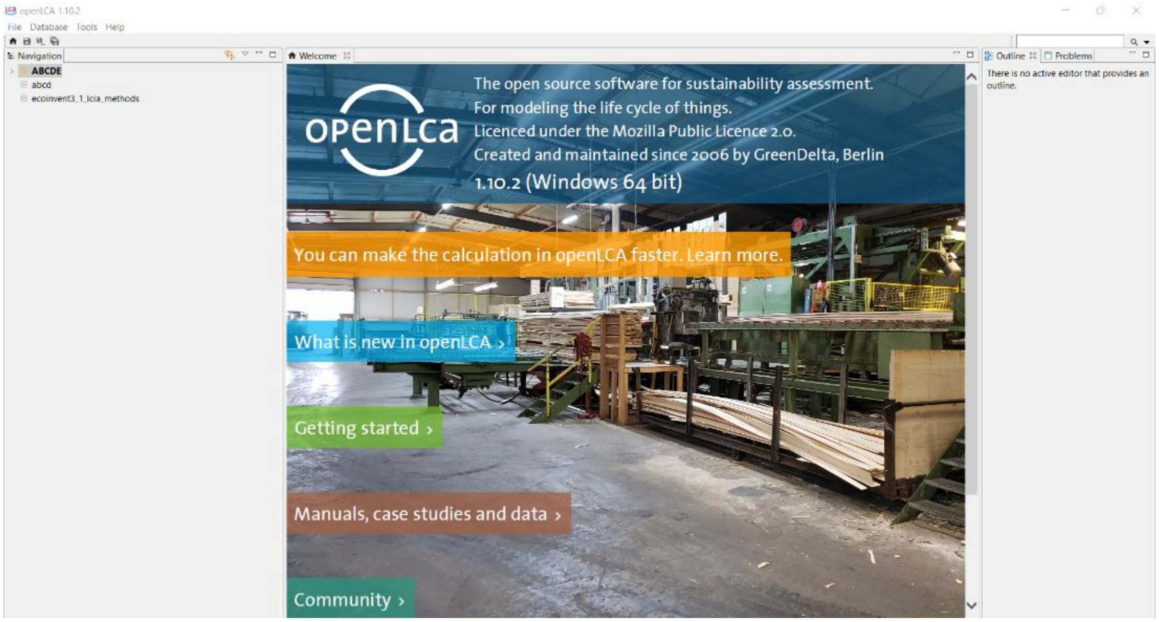

Fig. 4.1: openLCA software

4.2 PROCEDURE

First we have to open 'openLCA' software. Then, right click on the tab seen on the left side of the screen on the software and click on 'create new database'. Name the database as you like and select database type as 'local' and database content as 'complete reference data'. The database created contains main data, background data and indicators and parameters. The background data will be empty initially. To add background data we have to download databases in the computer. For this, we have to visit 'Open LCA NEXUS' website and download database. There will be free databases and also paid databases available. We can download free databases like 'Ecoinvent', 'Gabi':etc. After this, import the database to the software by right clicking on background data.

There are many levels of data available in the created database. They are (starting from the lowest) flows, processes, product systems and projects. Various flows are available in the software itself. Our primary job is to create the required processes with available flow data. For that, we have to create new process by right clicking on processes. For this work, we have two processes manufacturing and burning of the diesel fuel in the engine.

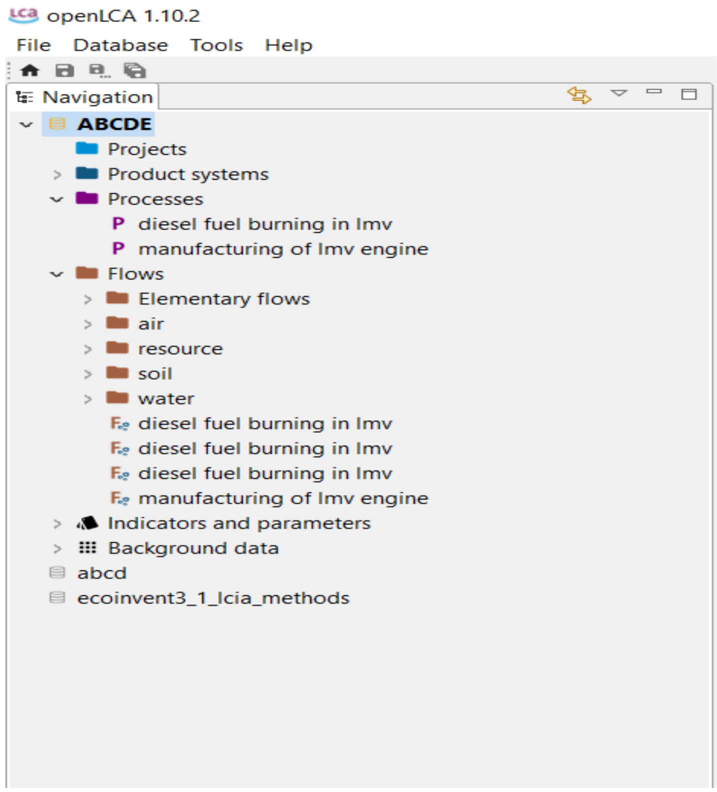

Fig. 4.2: Different data levels in openLCA

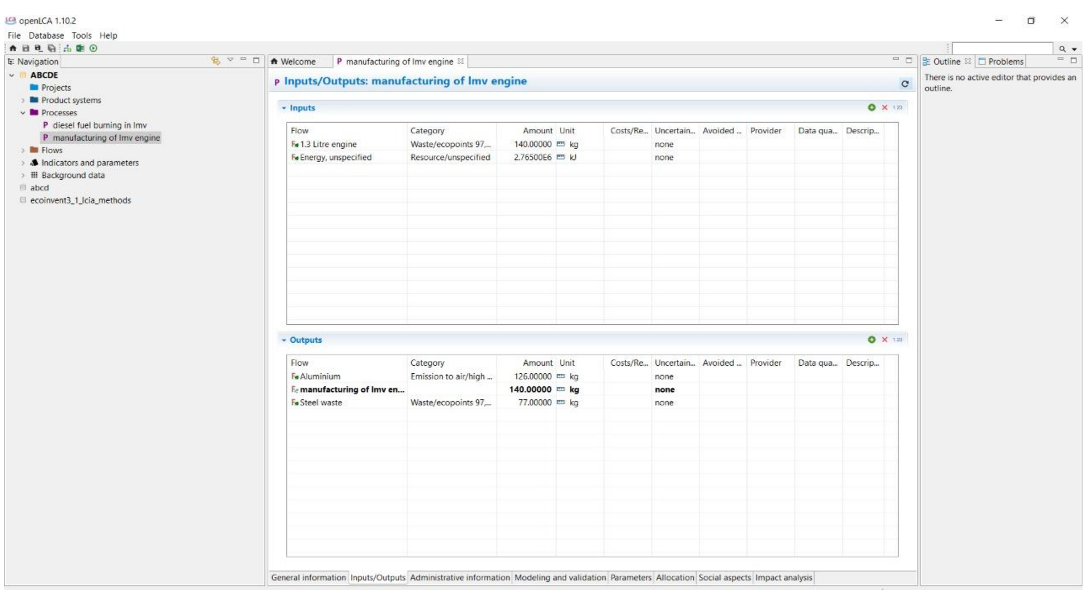

Fig. 4.3: Manufacturing process of LMV inputs and outputs

For the first process (manufacturing), we have to name it accordingly and put a tick mark on ‘create new flow for the process’. Then select reference flow property as ‘mass’. The mass of the engine is to be added as reference flow property. For adding inputs and outputs, we have to double click on the process. There appears general information menu. On the tab below we can see inputs/outputs. Click on that. As input we have to add the required processing energy and the outputs as steel and aluminium carbon emissions.

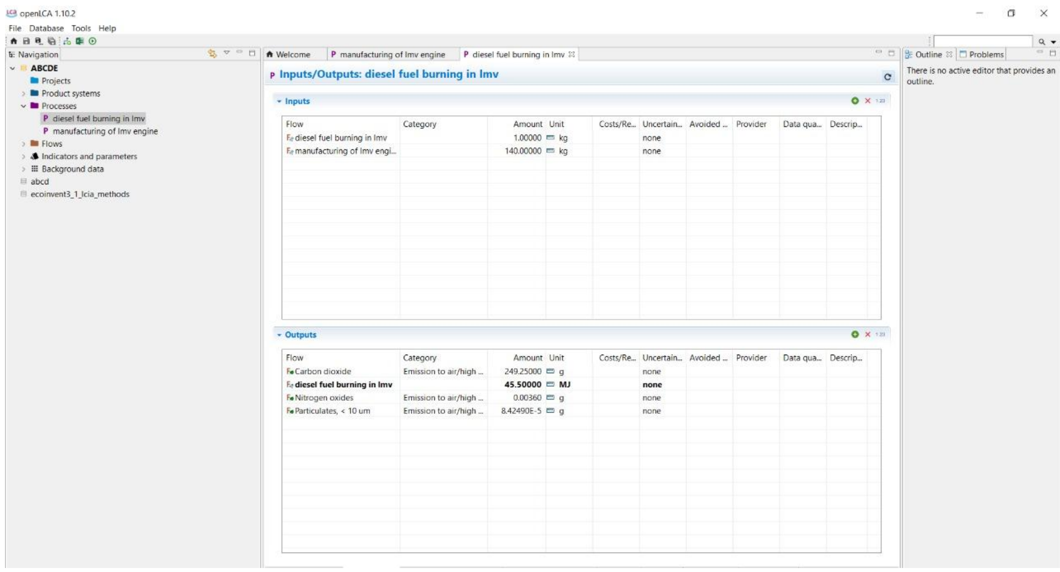

Fig. 4.4: Burning of diesel in LMV inputs and outputs

For diesel burning process, again we have to right click on processes and add new process. Here, we have to select volume as reference flow property and volume of diesel to be burned is be added as the value. Click on inputs/outputs and add the energy of diesel (calorific value) and the manufacturing process (since the processes are connected) as inputs and carbon di oxide, nitrogen oxides and particulate emissions as outputs.

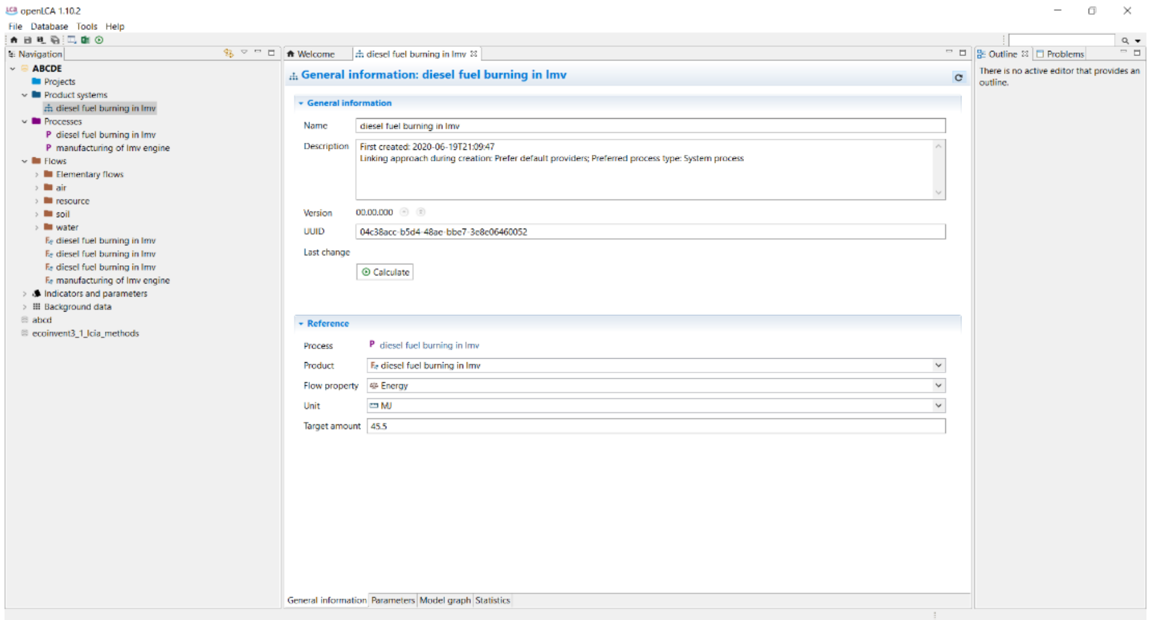

Fig. 4.5: Product system creation window

After finishing processes, we have to create a new product system by right clicking on product systems. In the menu appears select diesel burning process as the reference process and click finish. But, we have not added any 'impact assessment methods' in the indicators and parameters. Without adding that the data can't be run.

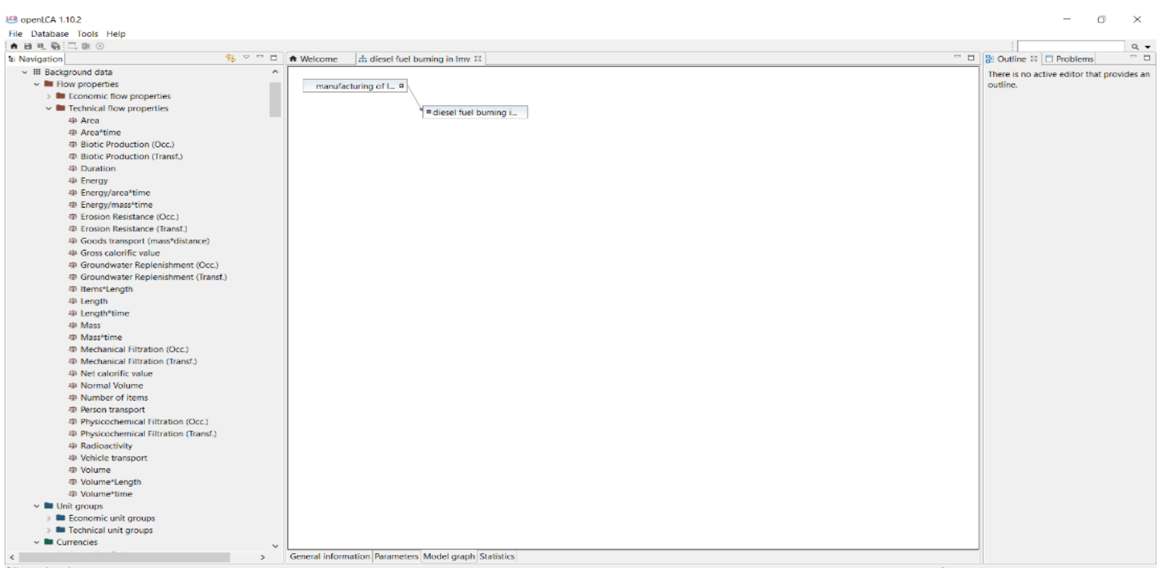

Fig. 4.6: Model graph of product system

For adding impact assessment method we have to import it from the background database. So, double click on the background database. Go to indicators and parameters and then to impact assessment methods. There will be a lot of impact assessment methods. We have to click on ‘export’ by right clicking on impact assessment methods. Then select the whole group of methods and click a folder to save these data. After this, double click on the new database we have previously created. Go to impact assessment methods from indicators and parameters. Right click and select ‘import’. Select the previously saved methods from the folder and click ‘finish’. Now, the impact assessment methods are imported.

Double click on the product system created. Now we can see a ‘calculate’ button and click on that. Now, a menu will appear select impact assessment method as ‘ReCiPe Midpoint (H)’. Click on ‘next’ and then ‘finish’. After some time, the results which are according to the environmental impacts will appear.

CHAPTER 5

RESULTS AND DISCUSSION

Results obtained from calculations in different phases of life cycle are as follows:

- **PRODUCTION PHASE**
  - Em = 2.765 *10^6 kJ
  - Cst = 77 kg
  - C_{Al} = 126 kg
- **USAGE PHASE**
  - EM_{CO2} = 249.25 g/J
  - EM_{NOX} = 0.0036 g/J
  - EM_{PM} = 8.4249 *10^-5 g/J
  - EM_{Total} = 249.2537142g/J
- **END OF LIFE**
  - E_{dp} = 5.18 * 10^4 kJ
  - End of life emissions are the least in the life cycle.
- The values obtained according to the equations adopted are satisfiable upto a certain extent.
- By finding out the emission factors for respective effluents using the predetermined data of fuel, the overall carbon footprints are obtained.
- The data's related to the `production' and `end of life' stages need to be obtained from a suitable industry for precise results.
- According to the values obtained from calculations, we have obtained the results in the 'openLCA' software, just by adding inputs and outputs and by following the entire procedure in the software.

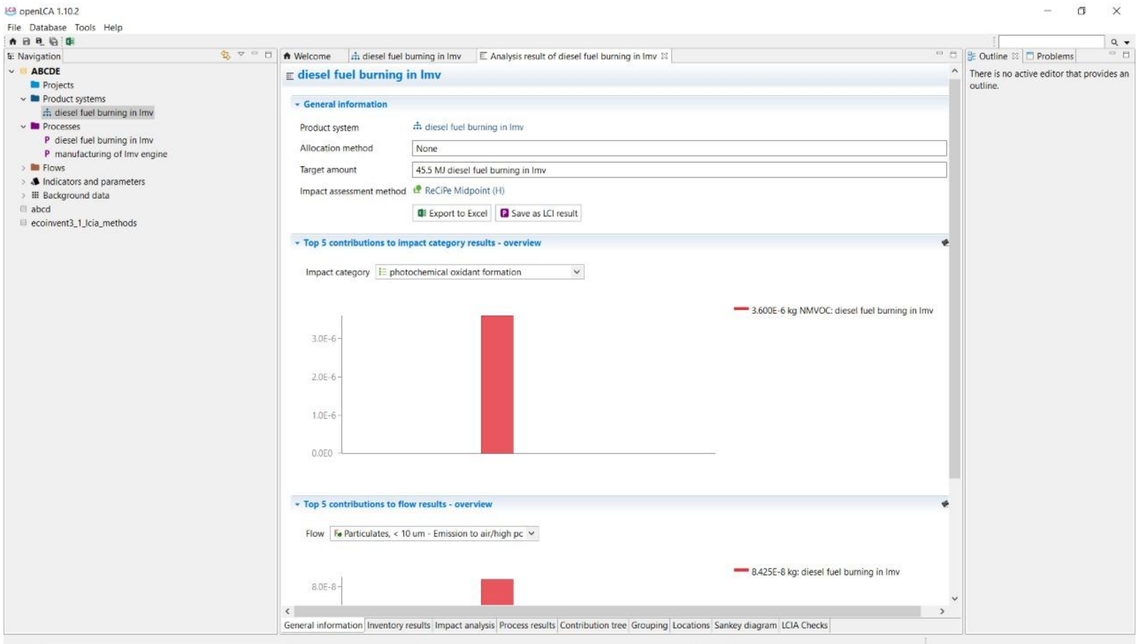

Fig. 5.1: Photochemical oxidant formation

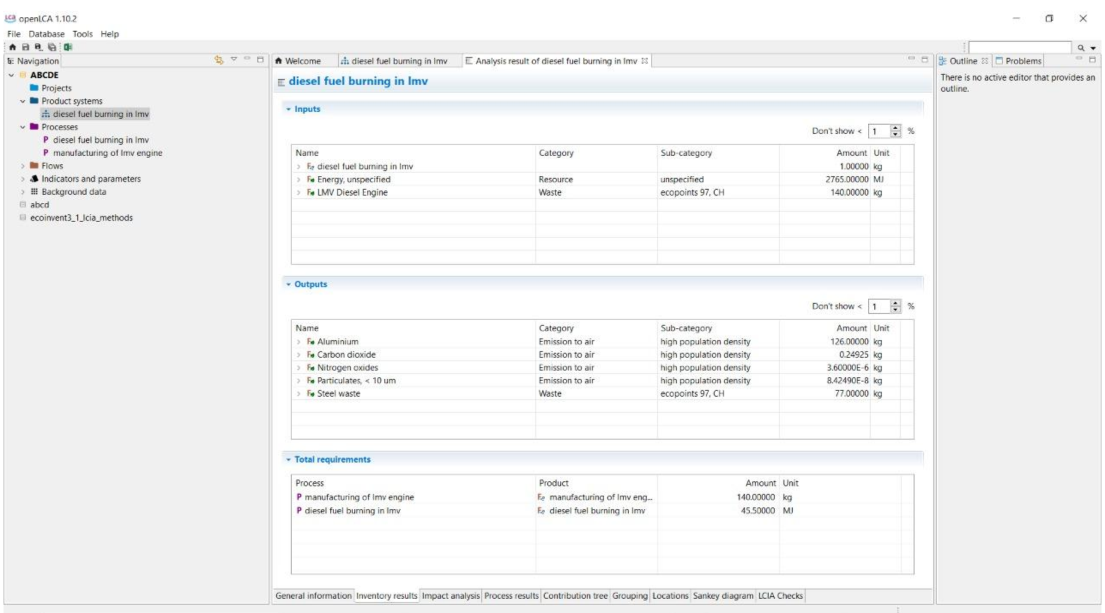

Fig. 5.2: Inventory analysis

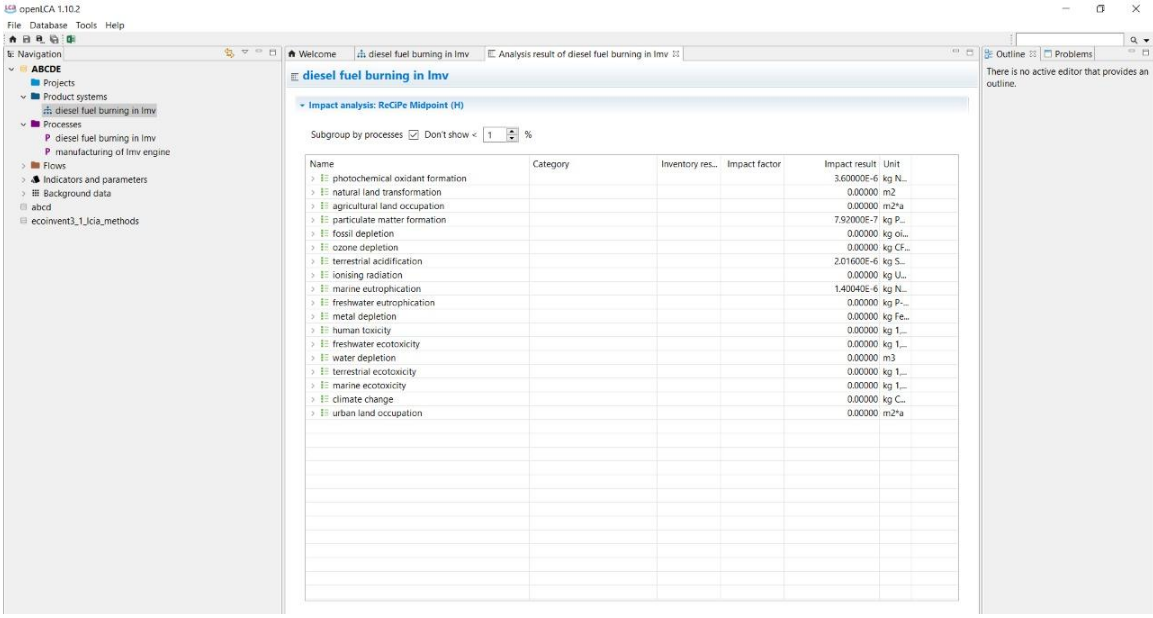

Fig. 5.3: Impact assessment

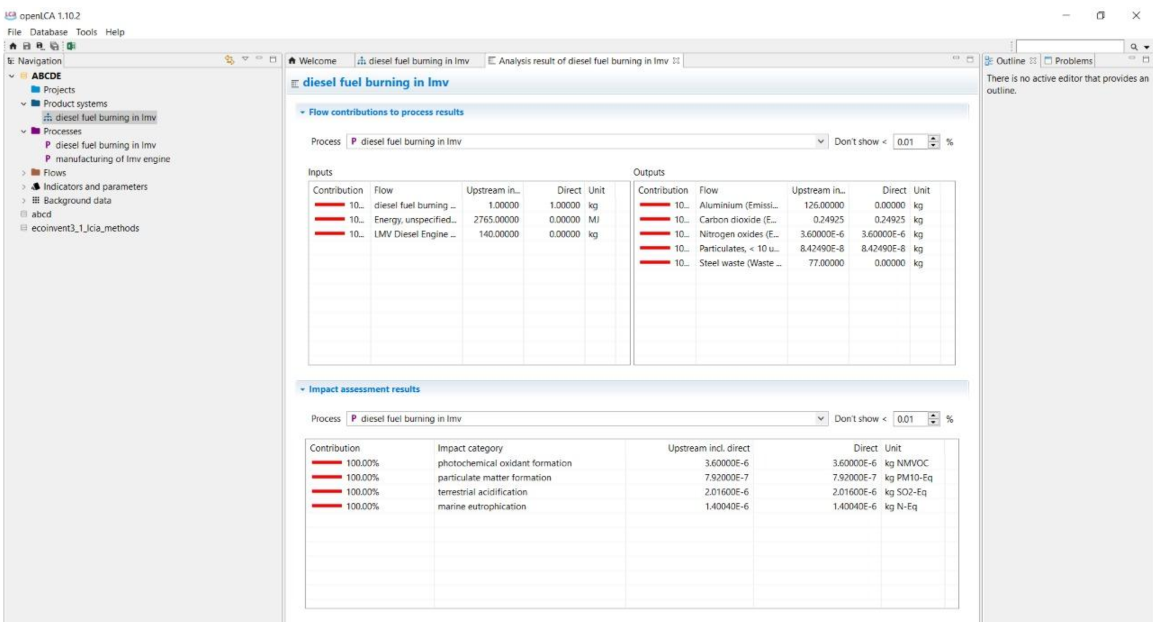

Fig. 5.4: Impact assessment results

By doing LCA using the software, we got the following results:

- Photochemical Oxidant formation = 3.6* 10^ -6 kg NMVOC
- Particulate Matter formation = 7.92 * 10^-7 kg PM10-Eq
- Terrestrial Acidification = 2.016 * 10^ -6 kg SO_2 Eq

- Marine Eutrophication = 1.4004* 10^ -6 kg N-Eq

Environmental burdens like ozone depletion are not present in the results due to the lack of sulphur content in the emission data considered.

CONCLUSIONS

Our study provides a broad assessment regarding the environmental burdens produced regarding the life cycle inventory analysis of a chosen LMV Diesel Engine. The analysis deals with the entire life cycle of the vehicles and the assessment is based on wide range of impact categories to both human and eco system health. We have analysed the impacts of different pollutants such as CO_2, NO_X, particulates over impact categories such as terrestrial acidification, marine eutrophication, photochemical oxide formation, particulate matter formation etc.

The total GHG emissions from the life cycle of an ICE vehicle, where the major hotspot areas are operation phase and production phase. The results of the impact assessment show that the chosen LMV Engine releases CO_2 emission more. This depends on the composition of fuel as well as the internal efficiency of the diesel engine. As mentioned above, ozone depletion is not taken into consideration due to the absence of sulphur particles in the chosen data from GREET manual.

The production phase gives an idea regarding the use of different material compositions such as steel and cast iron in the considered engine production. By using the formulas prescribed, it is found that steel being denser than aluminium has less carbon emissions (about 37.93%) compared to aluminium. Thus steel is slightly more preferable than aluminium in our case, although aluminium is fair. But the energy consumption during production stage is 2.765*10^6 kJ, which can be brought down by considering lightweight materials, so that energy consumption can be brought down significantly.

During the end of life phase there are no emissions arising from the engine as it is not operational. But some energy is required so as to carry out the disposal of the engine. By using a particular method we found out that the energy required for disposal was about 5.18*10^4 kJ. The disposal method chosen may vary from engine to engine as different manufacturers use different material composition for the engine.

Overall summary in brief:

- Of all the emissions calculated, CO_2 emission is the highest.

- 30 year average emission values are taken from GREET manual; so we have analysed the life of diesel engine for long running.
- Energy and speed of the vehicle are taken into consideration in emission. So emission of an average running vehicle is calculated.

SCOPE OF FUTURE WORK

- The life cycle assessment will be more accurate if primary data is available.
- Even though the production phase and end of life doesn’t contribute that much when compared to the usage phase in terms of emissions; considering these phases and by doing assessment of these phases by using primary data from industries can give us a more satisfactory result.
- Diesel engine becomes more reliant in heavy duty vehicles such as buses, trucks etc.
- Perfect impact assessment method is not available for the LCA study. If such method is available more accurate results will be obtained.
- Manufacturers can develop methods to reduce environmental burden after analysing LCA studies so as to attain sustainability.

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