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CO_2 emissions reduction by switching conference online: Uncertainty analysis of global air travel

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ABSTRACT

Ideally, primary data collection is recommended for every life cycle assessment (LCA) study. However, due to limited availability or accessibility to first-hand data, related sources of secondary data can be a good alternative in practice. In this work, the uncertainty of using secondary data from *the Ecoinvent Life Cycle Inventory* (LCI) database is illustrated with an LCA case study on global air travel. Inside the database, both parameters' basic uncertainty from measurements and additional uncertainty from data quality criteria are considered with the pedigree approach. The effect of updated pedigree matrix coefficients is also evaluated. Furthermore, the sensitivity with respect to the choice of system boundary is studied with a hotspot analysis for air travel. Outside the database, the uncertainty associated with mapping real world processes to those available in the database is analyzed. In particular, the influence of flight specific parameters, e.g. plane type and occupancy level, is assessed by comparing the International Civil Aviation Organizations (ICAO) carbon emissions calculator with database calculations. The results show that emissions calculated by ICAO generally lie on the lower end of confidence intervals provided by uncertainty analysis of the database, especially for very long-haul flights. Finally, for the LCA case study on air travel, a two-step method combining the advantages of both the ICAO calculator and the *Ecoinvent* database is proposed.

Keywords: life cycle assessment, life cycle inventory database, global air travel, uncertainty analysis, hotspot analysis

1. INTRODUCTION

The COVID-19 pandemic is significantly influencing human activities, energy consumptions and carbon dioxide (CO_2) emissions. Most conferences are switched to virtual online mode facing the pandemic. How much is its effect on the global CO_2 emissions? We present three papers in series using the International Conference of Applied Energy 2019 (more than 1000 participants from 57 countries/regions) as an example to calculate how much CO_2 emissions could be reduced by virtual conferences compared with conventional on-site conferences. This work, which is the last one in the three-paper series, serves to quantify the uncertainty of using secondary data from the *Ecoinvent* LCI database on LCA studies for air travel. Based on the database, uncertainty analysis is conducted to show variations in LCA calculations and hotspot analysis is performed to study emission distributions along the supply chain. The results are also compared with the ICAO carbon emissions

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calculator to reflect the influence of imperfect mapping between database activities and real-world processes. Finally, a two-step method to combine both sources of data is proposed.

2. METHODOLOGY

The *Ecoinvent* LCI database provides three linked system models that can be used to construct matrices for matrix-based LCA [1]. In this work, the cut-off model is used in results and discussion section, but it is worth mentioning that the methodology presented in this section can be applied to all system models in *Ecoinvent*. In matrix-based LCA, if the set of processes, environmental flows and impact indicators are denoted $\mathcal{P}$, $\mathcal{E}$ and $\mathcal{I}$ respectively, the technology matrix A is defined as

$$A = (a_{j,i})_{j,i \in \mathcal{P}}$$

where $a_{j,i}$ is the output of process j's reference product per unit operation of process i. The intervention matrix B is defined as

$$B = (b_{k,i})_{k \in \mathcal{E}, i \in \mathcal{P}}$$

where $b_{k,i}$ is the emission of environmental flow k per unit operation of process i. The characterization matrix C is defined as

$$C = (c_{l,k})_{l \in \mathcal{I}, k \in \mathcal{E}}$$

where $c_{l,k}$ is the characterization factor of impact indicator l per unit emission of environmental flow k. Finally, for any given demand vector $b = (b_i)_{i \in \mathcal{P}}$ where b_i represents the demand for reference product of process i, the corresponding impact can be assessed as

$$y = CBA^{-1}b$$

where $y = (y_l)_{l \in \mathcal{I}}$ and y_l is the value of impact indicator l.

Data used in LCA calculations are subject to uncertainty. Due to the lack of uncertainty information on impact assessment methods in their original documentations, *Ecoinvent* only quantifies uncertainty on exchange values, i.e. the coefficients in A and B matrices. In the database, the basic uncertainty associated with parameters' intrinsic variability can be modeled with one of the seven different statistical distributions provided by the database while the additional uncertainty associated with imperfect data quality is quantified with the five criteria in pedigree matrix. The two types of uncertainty can be combined via the pedigree approach [2]. For any given demand vector b and impact assessment method $l \in \mathcal{I}$, the uncertainty on its impact score y_l can be obtained from a Monte Carlo simulation.

The unit processes in the database often provide information on gate-to-gate LCIs, which facilitates further analysis on emission hotspots along the supply chain of a reference product. For any process $i \in \mathcal{P}$ and impact indicator $l \in \mathcal{I}$, denote the i^{th} column of A and the l^{th} row of C as A^i and C_l, respectively, and define demand vector b with one-hot encoding as

$$b_{i'} = \begin{cases} 1 & \text{if } i' = i \\ 0 & \text{otherwise} \end{cases} \qquad \forall i' \in \mathcal{P}$$

then $C_l B b$ calculates the impact from direct emissions per unit reference product of process i. The requirement for intermediate exchanges, i.e. reference products of other processes, by process i can be retrieved from A^i. For any nonzero non-diagonal element $a_{j,i}$ in A^i, similar one-hot demand vector with the j^{th} element equal to $-a_{j,i}$ and others zero can be defined for process j which is immediately upstream to process i. The entire procedure of calculating impact from direct emissions and creating demand vectors for upstream processes can be executed recursively until the entire supply chain is expanded with desired level of details.

3. RESULTS AND DISCUSSION

In order to illustrate the uncertainty of using secondary data from the *Ecoinvent* LCI database, an LCA case study on air travel is conducted. The raw data of cut-off system model including uncertainty quantification are retrieved from *Ecoinvent* v3.7 database [3] for building the A and B matrices. In this work, environmental impact is not explicitly assessed, instead, the total amount of fossil CO_2 emissions is reported.

As a recent effort to derive uncertainty factors for the pedigree matrix based on empirical studies, *Ecoinvent* has preliminarily proposed an updated version of pedigree matrix coefficients [4]. Together with the original version based on expert judgement that is currently in use [5], the results of uncertainty analysis on air travel are compared for both versions as shown in Fig 1. In the database, there exist four types of air travel with the functional unit as *person*km* and all of them are shown in Fig 1. The red crosses represent the total amount of fossil CO_2 emissions per person*km calculated from deterministic parameter values of A and B matrices. The black boxes represent results from the original version of pedigree coefficients while the blue backgrounds show those from the updated version of pedigree coefficients. Due to the very large variability of results from updated pedigree uncertainty factors, the outliers for blue boxes are not shown in the figure.

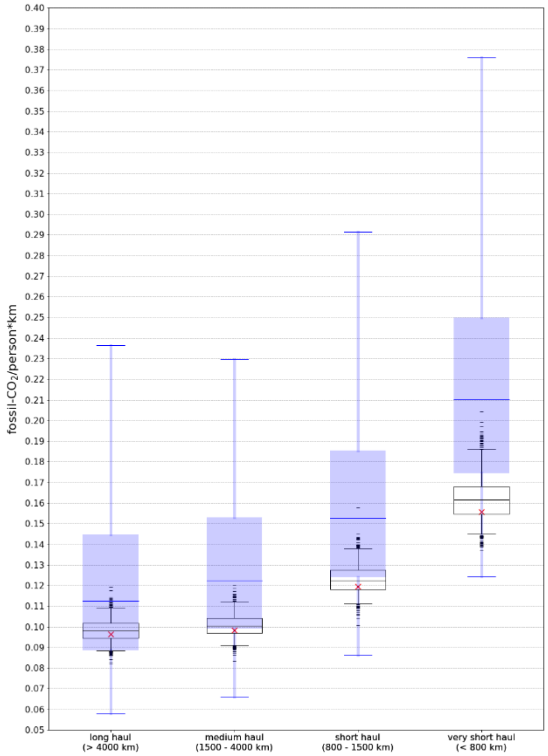

Fig 1. Boxplots for uncertainty analysis on four types of air travel (i.e. long haul, medium haul, short haul and very short haul)

As can be seen from Fig 1, the updated version of pedigree coefficients results in considerably larger uncertainty as compared to the original version. For long haul flights, the upper bound of 95% confidence interval obtained from the new version is approximately four times of the lower bound, making any calculation based on that result unlikely to be meaningful in real world. Therefore, only the original version of pedigree uncertainty factors is used in subsequent analysis when needed. Also, it is interesting to note that the deterministic values all lie below the medians obtained from Monte Carlo simulation in uncertainty analysis, which can be explained by the prevalent use of lognormal distribution that is asymmetric with positive support in the database.

In order to study the distribution of CO_2 emissions along the supply chain and evaluate the sensitivity with respect to the choice of system boundary, a hotspot analysis for long haul air travel is conducted as shown in Fig 2[1]. For the sake of numerical computation, 6000 person*km is used as product demand. The number on top of each red node is the index of that process in *Ecoinvent* v3.7 cut-off system model. The yellow nodes represent unexpanded emissions from the rest of supply chain and are connected to red nodes with dashed lines. The areas of red and yellow circles reflect the amount of direct CO_2 emissions for a process and unexpanded CO_2 emissions after a process, respectively.

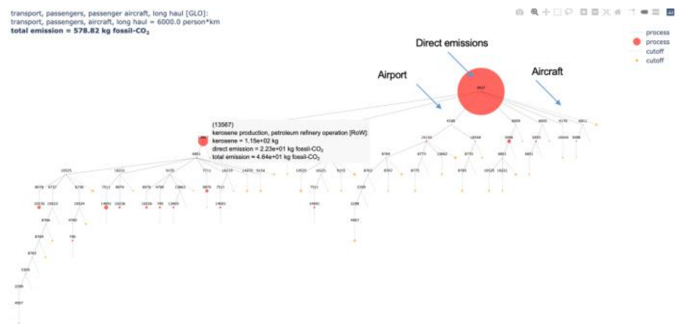

Fig 2. Tree plot for hotspot analysis on long haul air travel

For clarity, direct emissions, emissions from airport and aircraft production are annotated with arrows and texts in Fig 2. Other nodes directly connected to the root without annotation are fuel production activities at different geographies. As shown, direct emissions constitute the majority (86.4%) of total CO_2 emissions for long haul air travel while the remaining part is dominated by upstream fuel refinery. In comparison, the contributions of plane manufacturing (0.14%) and airport construction (1.48%) are negligible.

When using *Ecoinvent* as a source of secondary data for LCA studies on real world processes, uncertainty arises not only from the data and parameters inside the database, it can also come from the imperfect mapping between processes available in the database and the real world process of interest. Concretely, for the LCA case study on air travel in this work, although four types of flights with different distance ranges are provided by the *Ecoinvent* database, other flight specific parameters, e.g. plant type and occupancy level, are not explicitly modeled. Instead, global averages or fixed-value assumptions are used in the database, which could introduce additional uncertainty when using *Ecoinvent* to calculate CO_2 emissions for a real flight. For example, according to the ICAO carbon emissions calculator [6], a flight from Beijing, China (PEK) to Stockholm, Sweden (ARN) with a freight distance of 6688 km would result in direct CO_2 emissions of 286.6 kg/person. This value

[1] The interactive version of hotspot analysis visualizations for all four types of air travel with 6000 person*km demand is available at https://github.com/Yinan-LI/VCC.

corresponds to 0.0429 kg/person*km, which is lower than the value of 0.0833 kg/person*km (direct emissions only) for long haul flights calculated from *Ecoinvent*.

A closer analysis on the difference between ICAO and *Ecoinvent* calculations reveals that the overestimation of air travel emissions by *Ecoinvent* can be attributed to fuel consumptions. For the same flight example above, ICAO estimates flight fuel consumption to be 0.0136 kg/person*km while the estimation used by *Ecoinvent* for long haul flights is 0.0267 kg/person*km. With more flight specific parameters considered and real-world data involved, the ICAO calculator should provide a more accurate result, however, it also suffers from the following limitations. Firstly, the ICAO calculator only provides direct CO_2 emissions during air travel. Other types of environmental flows and indirect emissions are not considered. Secondly, only a single value is estimated by the calculator without any uncertainty quantification. Therefore, in order to combine the advantages of both the *Ecoinvent* LCI database and the ICAO carbon emission calculator, a two-step method is proposed. For fuel consumption, the more accurate source of ICAO calculator can be used while for LCIs (including but not limited to fossil CO_2) per unit fuel consumed, the more comprehensive source of *Ecoinvent* database can be used. Specially, given the fact that the ratios between CO_2 emissions and fuel consumption are almost the same for all four types of air travel in *Ecoinvent*, the 99% confidence interval for total CO_2 emissions per unit fuel consumption is estimated to be from 3.603 to 3.621 kg/kg for air travel.

4. CONCLUSION

In this work, the uncertainty of using secondary data from the *Ecoinvent* LCI database is systematically assessed with an LCA case study on air travel. Inside the database, the usage of new pedigree uncertainty factors would result in too large variations in LCA calculations, therefore not currently suggested. A hotspot analysis shows that the majority of CO_2 emissions in air travel comes from direct emissions during flights, while the remaining portion is dominated by upstream fuel refinery. Outside the database, mapping database activities to real world processes could also introduce additional uncertainty. For example, it is found that results of air travel CO_2 emissions based on *Ecoinvent* can be larger than those obtained from the ICAO carbon emissions calculator, which is attributed to the higher fuel consumption rate used in *Ecoinvent*. Finally, in order to combine the advantages of both sources, a two-step method which obtains flight fuel consumption from ICAO and calculates fuel-related LCIs with uncertainty quantification from *Ecoinvent* is proposed for future work.

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