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Framework for the Development of Thai Normalisation Factors for Life Cycle Assessment in Thailand

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Abstract

Life cycle assessment (LCA) has become a widely recognized method for evaluating the environmental performance of a product or system along its supply chain. Nowadays, site-dependent Life Cycle Impact Assessment (LCIA) methods have been developed and LCA results could therefore potentially reflect the local, national, and/or regional environmental conditions. In Thailand, site-dependent normalisation factors (NFs) which could support the local decision context have not been developed yet. The objectives of this study are to review underlying methodologies of the NFs in existing LCIA methods; and to establish a framework for the development of Thai NFs. Depending upon the spatial scales, four LCIA methods (ReCiPe 2016, EF 3.0, CML-IA baseline, and TRACI 2.1) were selected to be reviewed and considered when designing a framework. The theoretical approach for the NFs of the four selected LCIA methods is similar but the considered impact categories are different depending upon the spatial distribution and targeted environmental impacts. NFs from each LCIA method apply different reference inventory and year depending upon its spatial scale and data availability, and apply different approaches for data source selection. The selection of an appropriate reference system and representative year for the inventory, and data gap filling are essential criteria to develop NFs for life cycle assessment in Thailand. After the reference inventory is developed for the NFs of desired spatial scale (regional or national), the robustness of the inventory should be evaluated to reflect the actual impacts from each category. The developed framework could provide the required information for the future development of NFs and satisfy the required gap specific for Thailand. Besides, this framework is potentially applicable for other regions.

Keywords : Normalisation factors; Life cycle impact assessment; Thai spatially differentiated LCIA; Reference inventory; Data gap filling

Introduction

Life cycle assessment (LCA) has become a widely recognized method for evaluating the environmental performance of a product or system along its supply chain including raw materials extraction and processing, product manufacturing, distribution and usage, recycling, and/or final disposal. Life Cycle Impact Assessment (LCIA) is one of the key phases in undertaking LCA studies where the inputs and outputs of the elementary flows (i.e. environmental emissions, resource consumptions) are evaluated and allocated to impact categories related to human health, environment, and resource depletion. The results for each impact category obtained after LCIA are in complex units and it is hard to interpret for an audience who is not familiar with LCA. Then, ISO 14044 [1] includes an optional step of normalisation after characterisation which compares the magnitude of the various impact category indicator results to reference values.

Normalisation helps to bring the scores of various impact categories to a common reference scale. When assessing the environmental performance of a product or system, normalisation aims to compare the environmental impacts related to a product or system to the reference values on related impact categories of the reference system by showing them, for example, in person equivalents or person-years. As a result, the normalised results for each impact are in the same unit and it is easier for comparison between the different impact categories to support easy communication of the results. Normalisation factors (NFs) are calculated by using the regional or global inventories of emissions and resources as a reference system. According to the ISO guidelines, normalisation is regarded as optional. However, the application of NFs facilitates the interpretation of LCA results and communicating key results to decision-makers and policymakers.

Site-dependent LCIA methods such as TRACI in US, LIME in Japan, and IMPACT WORLD+ in Europe have been developed and widely applied nowadays. As a result, LCA results could actually reflect the local and regional environmental conditions. The application of LCA is also extensively increasing in Thailand as an evaluation and decision support tool in many sectors [2] but the site-dependent NFs for the impact categories which could support the local decision context have not been developed yet to communicate the results of LCA with the public effectively. Therefore, the objectives of this study are to review underlying methodologies of the NFs in existing LCIA methods; and to establish a suitable framework for the development of Thai normalisation factors for life cycle assessment in Thailand.

Material and Methods

Depending upon the different spatial distributions (i.e., national, regional, and global), four LCIA methods were selected to review in order to develop a framework for Thai NFs. ReCiPe 2016 (v1.05) midpoint method, Hierarchist version, which was created by the National Institute for Public Health and the Environment (RIVM), Radboud University, Norwegian University of Science and Technology and PRé Consultants, was selected for the global scale. Environmental Footprint initiative, EF 3.0 (v1.01) which was initiative introduced by the European Commission, and CML-IA baseline (v3.06) which was developed by the Centre of Environmental Science (CML) of Leiden University in the Netherlands, were selected for the regional scale. Tool for the

Reduction and Assessment of Chemical and other environmental Impacts, TRACI 2.1 (v1.05) developed by the U.S. Environmental Protection Agency, was selected for the national scale.

NFs from the above four LCIA methods were gathered from the latest version of the SimaPro software package (v9.2.0.1) and compared, then underlying methodologies of the NFs were also reviewed to identify the differences in each impact category of LCIA methods. The selection of data sources and reference inventory for each impact category from each LCIA method, and data gap filling strategies were reviewed to obtain spatial approaches from the different site-dependent LCIA methods. The evaluation of completeness and robustness of reference inventory were also reviewed. Then, a framework was designed for the development of Thai NFs for life cycle assessment.

Results and Discussion

According to the findings from our review, the NFs from the four selected LCIA methods apply similar theoretical approach, i.e., the impacts from the product system prior to normalisation are divided by the impacts of the reference system, but the considered impact categories are different depending on the spatial distribution and targeted environmental impacts. Eighteen impact categories are considered in ReCiPe 2016, sixteen impact categories are considered in EF 3.0, eleven impact categories are considered in CML-IA baseline, and ten impact categories are considered in TRACI 2.1 methods. Moreover, NFs from each LCIA method use different reference inventory and reference year depending on the data availability and targeted environmental impacts (**Table 1**). Therefore, NFs differ not only in figures but also in its representative substances (**Table 2**). Different approaches for data source selection are applied such as "Guidelines for data source prioritisation and data estimation" by Sleeswijk et al. [3], and "Hierarchical approach" by Sala et al. [4]. For example, NFs for ozone formation in ReCiPe 2016 considered for both human health and terrestrial ecosystems are 4.86E-02 person/kg NO_x eq. and 5.63E-02 person/kg NO_x eq.; but NFs for the similar impact category in EF 3.0, CML-IA baseline and TRACI 2.1 are 2.46E-02 person/kg NMVOC eq., 5.78E-10 person/kg C_2H_4 eq. and 7.18E-04 person/kg O_3 eq., respectively. Furthermore, EF 3.0, CML-IA baseline and TRACI 2.1 do not distinguish the sub-categories on human health and terrestrial ecosystems for ozone/smog formation.

Table 1 Overview of LCIA methods

LCIA method	No. of Impact category	Reference region	Reference year	Reference
ReCiPe 2016 (v1.05)	18	Global	2010	[5]
EF 3.0 (v1.01)	16	Global	2010	[6]
CML-IA baseline (v3.06)	11	Europe (EU25+3)	2000	[3]
TRACI 2.1 (v1.05)	10	USA	2008	[7]

Data on environmental releases and extractions that are necessarily required for the normalisation study are most often deficient for some geographical and temporal scales especially for developing countries. Therefore, data gap filling is inevitable in NFs development. However, explicit criteria must be applied to the data sources selection and data gap filling for consistency. Sleeswijk et al. [3] applied the factors such as GDP (gross domestic product) for the industrial production and release, crop production area for the crop-dependent ammonia emissions and pesticide use, population magnitude for the human waste production of N and P, nuclear power capacity for the release of radioactive substances, and estimated length of populated coastline for the metal releases in the marine environment, respectively. On the other hand, Sala et al. [8] applied more specific extrapolation methods for each specific emission and release, for instance, non-methane volatile organic compounds (NMVOC) breakdown estimates, ozone-depleting substances, toxic airborne emissions, greenhouse gas emissions, and so on. NFs from four LCIA methods are presented in **Table 2** and the main data sources applied for NFs are also presented in **Table 3**. After data gap filling, the potential of uncertainty in quantifying of NFs may arise therefore the robustness of reference inventory is evaluated for the quality and reliability of NFs. Then, NFs are computed for each impact category from the environmental performance of the product or system prior to normalisation and the selected reference inventory.

After reviewing the underlying methodologies of the NFs in the existing four LCIA methods, a framework is designed in which some parts are adopted from Sleeswijk et al. [3] and Sala et al. [4]. A designed framework for the development of Thai NFs is presented in **Figure 1** which includes goal and scope definition, selection of data sources and reference year, data gap filling, reference inventory evaluation, and quantification of Thai NF.

1. Goal and scope definition

Goal and scope should be clearly defined to establish the NFs by considering the intended application, spatial and temporal scales, and appropriate LCIA methods in the region. In addition, another important thing to consider is the uncertainties that could be derived from the inconsistency of reference spatial scale of the reference inventory and the intended study area, inconsistence LCIA modelling and the number of considered substances in the model [9]. When quantifying NFs, choice of LCIA methods can yield significantly different results even when applying the same inventory [10], which could lead to bias the decision-making process. For this reason, the LCIA method for the reference inventory for Thai NFs, and the product system prior to normalisation should be consistent for enhancing the robustness of the NFs.

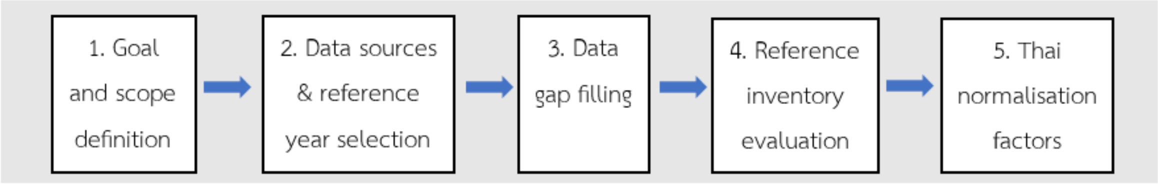

Figure 1 Framework for the development of Thai Normalisation Factors

Table 2 Normalisation factors of four different spatial scale LCIA methods

Impact Category	Normalisation Factors			
	ReCiPe 2016 (v1.05) (Global scale)	EF 3.0 (v1.01) (Regional scale)	CML-IA baseline (v3.06) (Regional scale)	TRACI 2.1 (v1.05) (National scale)
Global warming	1.25E-04 person/kg CO_2 eq	1.24E-04 person/kg CO_2 eq [a]	1.92E-13 person/kg CO_2 eq	4.13E-05 person/kg CO_2 eq
Photochemical ozone formation	4.86E-02 person/kg NO_x eq [b] 5.63E-02 person/kg NO_x eq [e]	2.46E-02 person/kg NMVOC eq	5.78E-10 person/kg C_2H_4 eq [c]	7.18E-04 person/kg O_3 eq [d]
Ozone depletion	1.67E+01 person/kg CFC-11 eq	1.86E+01 person/kg CFC-11 eq	9.80E-08 person/kg CFC-11 eq	6.20E+00 person/kg CFC-11 eq
Ionizing radiation	2.08E-03 person/kBq Co-60 eq	2.37E-04 person/ kBq U-235 eq	-	-
Human carcinogenic toxicity	9.71E-02 person/kg 1,4-DB eq	5.92E+04 person/CTUh	2.00E-12 person/kg 1,4-DB eq	1.90E+04 person/CTUh
Human non-carcinogenic toxicity	3.20E-05 person/kg 1,4-DB eq	4.35E+03 person/CTUh		9.52E+02 person/CTUh
Fine particulate matter formation	3.91E-02 person/kg $PM_{2.5}$ eq	1.68E+03 person/disease incidences [f]	-	4.12E-02 person/kg $PM_{2.5}$ eq [g]
Acidification	2.44E-02 person/kg SO_2 eq [h]	1.80E-02 person/mol H^+ eq	5.94E-11 person/kg SO_2 eq	1.10E-02 person/kg SO_2 eq
Terrestrial ecotoxicity	6.58E-05 person/kg 1,4-DB eq	-	8.61E-12 person/kg 1,4-DB eq	9.03E-05 person/CTUe
Freshwater ecotoxicity	3.97E-02 person/kg 1,4-DB eq	2.34E-05 person/CTUe	4.79E-12 person/kg 1,4-DB eq	
Marine ecotoxicity	2.30E-02 person/kg 1,4-DB eq	-	2.25E-14 person/kg 1,4-DB eq	
Terrestrial eutrophication	-	5.66E-03 person/mol N eq	5.40E-11 person/kg PO_4^{3-} eq	4.63E-02 person/kg N eq
Freshwater eutrophication	1.54E+00 person/kg P eq	6.22E-01 person/kg P eq		
Marine eutrophication	2.17E-01 person/kg N eq	5.12E-02 person/kg N eq		
Land use	1.62E-04 person/m^2a crop eq	1.22E-06 person/Pt	-	-
Water consumption	3.75E-03 person/m^3	8.72E-05 person/m^3 water eq of deprived water	-	-
Mineral resource scarcity	8.33E-06 person/kg Cu eq	1.57E+01 person/kg Sb eq [i]	-	-
Fossil resource scarcity	1.02E-03 person/kg oil eq	1.54E-05 person/MJ [j]	-	5.31E-05 person/MJ surplus [k]
Abiotic depletion	-	-	1.66E-7 person/kg Sb eq	-
Abiotic depletion (fossil fuels)	-	-	2.85E-14 person/MJ	-

[a] Climate change; [b] Ozone formation, Human health; [c] Photochemical oxidation; [d] Smog; [e] Ozone formation, Terrestrial ecosystems; [f] Particulate matter; [g] Respiratory effects; [h] Terrestrial acidification; [i] Resource use, minerals and metals; [j] Resource use, fossils; [k] Fossil fuel depletion.

Table 3 The main data sources for normalisation factors from four different spatial scale LCIA methods [3, 5-7]

Impact category	Main data sources			
	ReCiPe 2016 (v1.05) (Global scale)	**EF 3.0 (v1.01) (Regional scale)**	**CML-IA baseline (v3.06) (Regional scale)**	**TRACI 2.1 (v1.05) (National scale)**
Global warming	- United Nations Framework Convention on Climate Change - Netherlands Environmental Assessment Agency	- United Nations Convention on Climate Change [a] - Emission Database for Global Atmospheric Research [a]	- United Nations Framework Convention on Climate Change	- U.S. Environmental Protection Agency Inventory
Photochemical ozone formation	- European Monitoring and Evaluation Programme [b] - Netherlands Environmental Assessment Agency [e]	- Emission Database for Global Atmospheric Research	- European Monitoring and Evaluation Programme [c]	- National Emissions Inventory and Data [d]
Ozone depletion	- United Nations Environment Programme - Environment Canada - National Institute of Technology and Evaluation (Japan)	- Centre for Australian Weather and Climate Research	- World Meteorological Organization	- U.S. Greenhouse Gas Emissions and Sinks
Ionizing radiation	- Environment Agency (London)	- United Nations Scientific Committee on the Effects of Atomic Radiation - European Commission's Radioactive Discharges Database	-	-
Human carcinogenic toxicity Human non-carcinogenic toxicity	- National Pollutant Inventory (Australia) - European Monitoring and Evaluation Programme - Environment Canada - National Institute of Technology and Evaluation (Japan) - U.S. Environmental Protection Agency	- Technical report from LC-Impact project [11]	- European Monitoring and Evaluation Programme	- National Emissions Inventory and Data, Toxic Release Inventory - National Emissions Inventory and Data, Toxic Release Inventory
Fine particulate matter Formation	- European Monitoring and Evaluation Programme - Netherlands Environmental Assessment Agency	- Emission Database for Global Atmospheric Research [f]	-	- National Emissions Inventory and Data [g]
Acidification	- European Monitoring and Evaluation Programme [h] - Food and Agriculture Organization of the United Nations [h] - Netherlands Environmental Assessment Agency [h]	- Emission Database for Global Atmospheric Research	- European Monitoring and Evaluation Programme	- National Emissions Inventory and Data

[a] Climate change; [b] Ozone formation, Human health; [c] Photochemical oxidation; [d] Smog; [e] Ozone formation, Terrestrial ecosystems; [f] Particulate matter; [g] Respiratory effects; [h] Terrestrial acidification.

Table 3 The main data sources for normalisation factors from four different spatial scale LCIA methods (cont.) [3, 5-7]

Impact category	Main data sources: ReCiPe 2016 (v1.05) (Global scale)	EF 3.0 (v1.01) (Regional scale)	CML-IA baseline (v3.06) (Regional scale)	TRACI 2.1 (v1.05) (National scale)
Terrestrial ecotoxicity	- United Nations Environment Programme - Food and Agriculture Organization of the United Nations - Central Science Laboratory (York) - Datch Emission Register	-	- United Nations Environment Programme - Food and Agriculture Organization of the United Nations	- National Emissions Inventory and Data, Toxic Release Inventory
Freshwater ecotoxicity		- Technical report by the Joint Research Centre		
Marine ecotoxicity		-		
Terrestrial eutrophication	-	- Emission Database for Global Atmospheric Research - Food and Agriculture Organization of the United Nations – Statistics Division	-	- National Emissions Inventory and Data - U.S. Department of Agriculture
Freshwater eutrophication	- Food and Agriculture Organization of the United Nations		- Food and Agriculture Organization of the United Nations	
Marine eutrophication			-	
Land use	- World Resources Institute	- Food and Agriculture Organization of the United Nations – Statistics Division - National Aeronautics and Space Administration (U.S.A)	-	-
Water consumption	- AQUASTAT - FAO's Global Information System on Water and Agriculture	- AQUASTAT - FAO's Global Information System on Water and Agriculture - Organisation for Economic Co-operation and Development	-	-
Mineral resource scarcity	- International Energy Agency - United States Geological Survey	- United States Geological Survey [i] - British Geological Survey [i] - World Nuclear Association [j] - International Energy Agency [j]	-	-
Fossil resource scarcity			-	- U.S. Department of Energy [k]
Abiotic depletion	-	-	- US Geological Survey, Europe's environment: statistical compendium for the second assessment - International Energy Agency	-
Abiotic depletion (fossil fuels)	-	-		-

[i] Resource use, minerals and metals; [j] Resource use, fossils; [k] Fossil fuel depletion.

2. Selection of data sources and reference year

The reference inventory is the most influential part for the NFs to reflect the actual environmental conditions of the region. Uncertainties and possible biases are mainly related to the data used for the reference inventory calculation and its characterisation factors [12]. Moreover, different data sources could be available on the same emission and extraction for some impact categories. For this reason, emissions to air, water, soil, and resource extractions are needed to prioritise and process from the most relevant reliable data sources. The coverage of the data source, completeness of the time series, coverage of sectors responsible for the emissions, the existence of the review and quality assessment process, and the timing of the updates are the important criteria that should be considered when selecting the data sources. "Hierarchical approach" by Sala et al. [4] which provides the ranking of distinct datasets in order of preference, is the most updated and could be applied for Thai reference inventory.

Another possible bias could arise when the coverage of environmental flows varies between the reference inventory and inventory of the product system prior to normalise. For instance, a substance which derives characterised environmental impacts of the product system is not part of the reference inventory, and that substance is also a strong contributor to the system, which would be largely overestimated the result of normalisation. Therefore, the completeness of the reference inventory is crucial to alleviate the bias.

After the data sources selection, a reference year should be selected by the available data sources for all impact categories considered in the reference inventory to avoid bias. The most recent year with available data sources is strongly recommended to reflect the current condition of the impact categories in Thailand.

3. Data gap filling

Incompleteness of emission data for the reference inventory could lead bias to over or underestimation of the NFs. When some substance emissions are missing and only available for years other than the targeted reference year, the data gap filling should be performed by applying justification and extrapolation. For instance, if data is not available for the selected year, the sources could be justified in the following orders (i) data related to years which is closely differ from the targeted reference year coming from the primary source; (ii) data for targeted reference year from an alternative source; and (iii) if data is unavailable from an alternative source, a year that is different from the targeted reference year is selected [4], however we need to put caveats when interpreting the results. The emissions that do not vary significantly between the reported year and chosen reference year could be obtained by performing data gap filling.

According to the reviewed LCIA methods, different types of extrapolations were performed depending on the impact categories. Some examples are CO_2 emission-based extrapolations in which CO_2 emissions are considered as the scaling factor [13] and GDP-based extrapolations in which GDP is assumed to be related to the industrial production and the relative releases [3]. However, Sala et al. [8] applied a more specific estimation strategies and data gap filling method for each specific emission and release e.g. estimation for non-methane volatile organic compounds (NMVOC) and ozone-depleting substances, which could be appropriate for the Thailand region. The reference for some substance emissions would not be regionally defined. The application of extrapolations from global normalisation references is recommended in which inventory data cover the list of elementary flows available for each impact category [14].

4. Reference inventory evaluation

The evaluation of reference inventory is needed to ensure the robustness of the inventory after the data gap filling. The potential of uncertainty in the calculation of NFs may arise when applying the extrapolations or justifying the data gap in the reference inventory. Therefore, the robustness of inventory should be assessed by considering both the combination of different sources and the adoption of extrapolation strategies and mention qualitatively to support a better interpretation of the LCA results. The inventory data should be covered in the list of elementary flows available in the International Reference Life Cycle Data System (ILCD) of each impact category for its completeness and the quality of data should be assessed by ranking according to the "Criteria for evaluating the robustness of the global NFs" reported by [15].

The environmental flows for some impact categories such as climate change and acidification are monitored globally as a result the coverage of reference inventory for the environmental flows in these impact categories is relatively complete and reliable when compare with the toxicity related impart categories which include limited number of well monitored environmental flows [16]. Therefore, we need to put caveats when evaluating the inventory.

5. Quantification of Thai NFs

According to ISO 14044 [1], NFs could be quantified from the total environmental loads of reference area on a per capita basis as shown in the following **Eq. (1).** The reference population for Thailand should be used the same year with reference inventory to reflect the actual impact for each impact category from each capita. The population data for the Thailand in selected reference year could be obtained from the National Statistical Office, Thailand.

$$NF = 1 / (I_{reference} \times N_{population}) \quad \text{Eq. (1)}$$

Where; NF = normalisation factors for the impact category;

$I_{reference}$ = impact scores from the reference system;

$N_{population}$ = Thailand population in the reference year.

Conclusions

The considered impact categories for four different LCIA are different depending on their spatial distribution and targeted environmental impacts. NFs from each LCIA method apply different reference inventory and year depending on its spatial distribution and data availability, and also applied different approaches for data source selections. Data gap filling is inevitable in the NFs development. Therefore, explicit criteria must be applied to the data source selection and data gap filling for consistency. The reference inventory is the most influential part of the NFs. Therefore, environmental releases and extractions should be prioritised and processed from relevant reliable sources when establishing the reference inventory for Thailand. The selection of an appropriate reference system and representative year for the inventory and data gap filling are essential criteria to establish a framework for the development of Thai NFs. After the reference inventory is developed for the NFs of desired spatial scale (regional or national), the coverage completeness and robustness of the inventory should be evaluated to reflect the actual impact from each impact category. The developed framework could provide the required information for the future development of NFs and fulfil the required gap for the Thailand region besides it could also apply for the other region.

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