Life Cycle Assessment:
Impact Assessment & Uncertainty Implications

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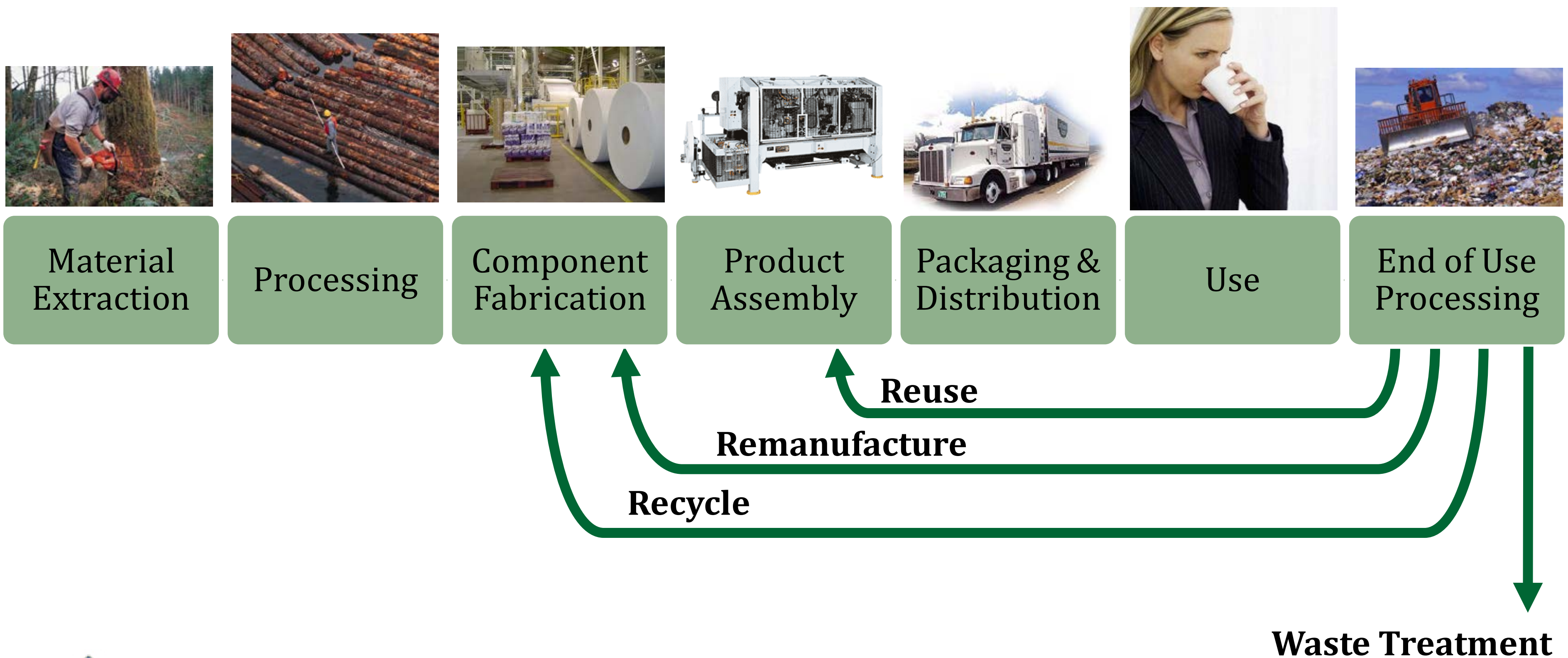
Life Cycle Assessment

Life Cycle Assessment (LCA) is a technique used to quantify the environmental impact of a product from raw material acquisition through end of life disposition (cradle-to-grave)



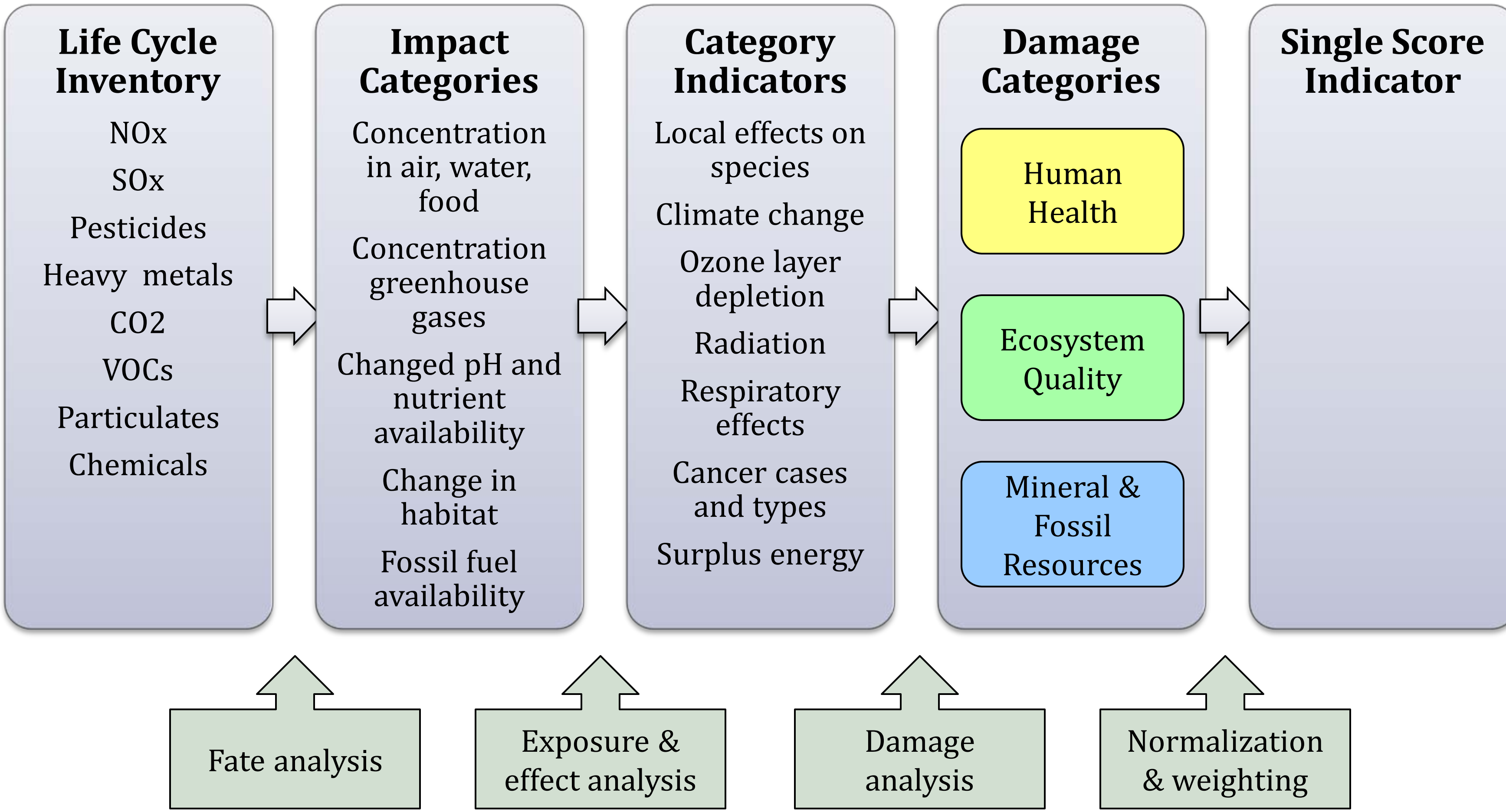
LCA Methodology

- A Life Cycle Assessment is carried out in four distinct phases: (ISO 14040, 14044)
  - Step 1: Goal definition and scoping. Identify the LCA's purpose, the products of the study, and determine the boundaries. (what is and is not included in the study)
  - Step 2: Life-cycle inventory. Quantify the energy and raw material inputs and environmental releases associated with each life cycle phase.
  - Step 3: Impact analysis. Assess the impacts on human health and the environment.
  - Step 4: Report results. Evaluate opportunities to reduce energy, material inputs, or environmental impacts at each stage of the product life-cycle.

Step 3: Impact Assessment

- Converts the inventory into impact categories or end points which explain the environmental effect
- Impact categories may include: carcinogens, respiratory organics and inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, fossil fuels
- Can apply weights to impact categories

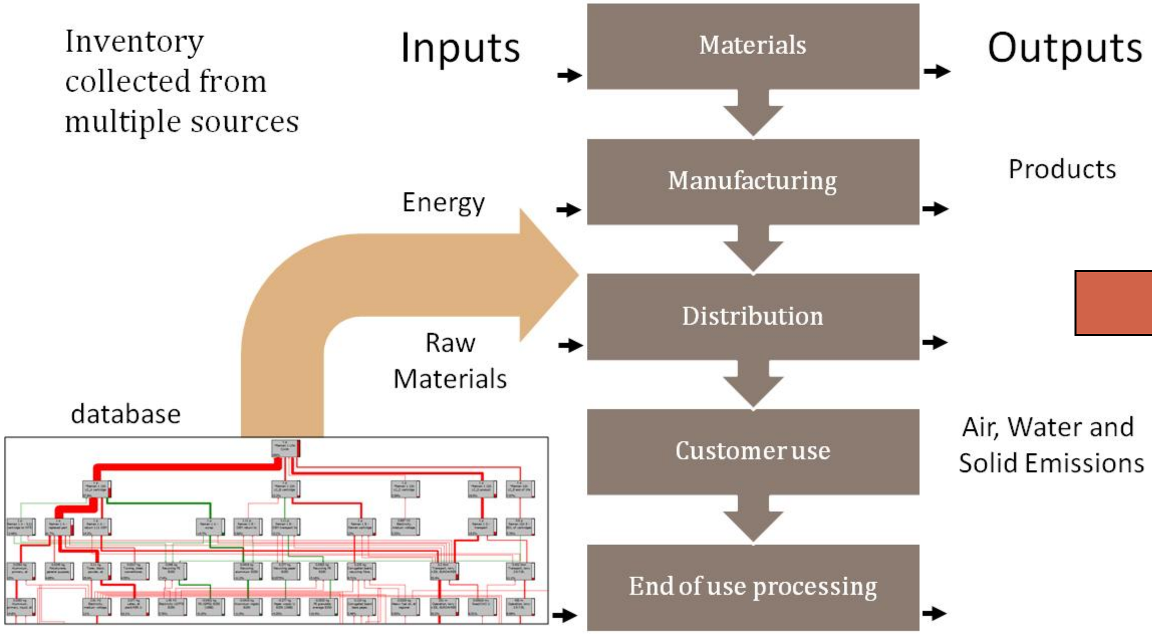
Impact Assessment



Conducting Impact Assessments

1. Select impact categories
2. Category indicators
3. Characterization models
4. Classification
5. Categorization
6. Optional aspects
   - Normalization
   - Grouping
   - Weighting

Life Cycle Inventory



Releases to air	Aldehydes, unspecified	µg	4.41E-08
Releases to soil	Aldrin	ng	3.02E-09
Raw material inputs	Aluminium, 24% in bauxite, 11% in crude ore, in ground	mg	8.07E-09
Releases to air	Aluminum	mg	4.9E-259
Releases to soil	Aluminum	mg	9.51E-09
Releases to air	Ammonia	mg	1.44E-06
Releases to air	Ammonium carbonate	µg	8.77E-08
Releases to water	Ammonium, ion	g	8.56E-09
Raw material inputs	Anhydrite, in ground	mg	2.62E-07
Releases to air	Antimony	µg	4.9E-259
Releases to soil	Antimony	ng	6.39E-11

Selecting impact categories, category indicators, & characterization models

- Impact categories: represents environmental issues of concern which life cycle inventory may be assigned
  - ie. fossil fuels, acidification, eutrophication, carcinogens, climate change
- Category indicators: quantifiable representation of an impact category
- Characterization models: mathematical models that convert life cycle inventory results to common units within each impact category

Term	Example
Impact category	Climate change
Category indicator	Infrared radiative forcing
Characterization model	Baseline model of 100 years of the Intergovernmental Panel on Climate Change

Example from ISO 14044 4.4.2.2.2

Classification

- Process where life cycle inventory results are assigned to impact categories
- Consider results that
  - Are exclusive to one impact category
    - ie. ozone may only contribute to ground level ozone formation
  - May relate to more than one impact category
    - ie. SOx may contribute to human health and acidification

Characterization

- Process that converts life cycle inventory results to common units so they can be aggregated

Impact categories & units	
Carcinogens	kg C2H3Cl eq
Non carcinogens	kg C2H3Cl eq
Respiratory inorganics	kg PM2.5 eq
Ionizing radiation	Bq C-14 eq
Ozone layer depletion	kg CFC-11 eq
Respiratory organics	kg C2H4 eq

Characterization Model

Damage Category & Unit
Human Health DALY (disability adjusted life years)

Example from Impact 2002+

Normalization

- Optional according to ISO
- Measure of the magnitude of the indicator results relative to a reference point
- Typical reference values:
  - Total inputs and outputs for a given area
  - Total inputs and outputs for a given area per capita
  - Total inputs and outputs in a baseline scenario
- ie. Impact 2002+ results are normalized by dividing the impact per unit of emission by the total impact of all substances of the specific category for which characterization factors exist, per person per year (for Europe).

Grouping

- Optional according to ISO
- Assigning impact categories to one or more sets
- May involve sorting or ranking
- Based on value choices
- May involve sorting impact categories by specific characteristics or ranking categories in a hierarchy

Weighting

- Optional according to ISO
- Converting indicator results of different impact categories by numerical factors based on value choices
- User or impact assessment method decides which impacts are more/less important
- Ie. Impact 2002+ weighs human health, ecosystem quality, climate change, and resources equally; EcoIndicator 99 weighs human health and ecosystem quality twice as important as resources

Impact Assessment Methods

- Mathematical models developed by researchers to calculate impact categories & category indicators
- May involve normalization and/or weighting
- Based on flow of emissions to environmental media and people

IPCC Global Warming Potential

- Used to calculate global warming potential
- Developed by International Panel on Climate Change
- Considers airborne emissions
- Expressed in kg CO2 equivalents
- Climate change factors with a timeframe of 20, 100 or 500 years
- Normalization and Weighting are not part of this method
- Climate Change 2007. IPCC Fourth Assessment Report. The Physical Science Basis. http://www.ipcc.ch/ipccreports/ar4-wg1.htm

TRACI 2

- Used to assess a substance at the impact category level only – does not include damage assessment
- Tool for the Reduction and Assessment of Chemical and other Environmental Impacts developed by US EPA
- Developed specifically for the US, using data from US locations for acidification, smog formation, eutrophication, human cancer, human non cancer, and human criteria effects
- More information: http://www.epa.gov/nrmrl/std/traci/traci.html

Impact Categories
Global warming
Acidification
Carcinogens
Non carcinogens
Respiratory effects
Eutrophication
Ozone depletion
Ecotoxicity
Smog

Impact 2002+

- Midpoint and end point method developed at the Swiss Federal Institute of Technology – Lausanne
- Includes characterization, damage assessment, normalization and evaluation
- Translates life cycle inventory to midpoint (impact categories) and combines those to form damage categories
- Some impact categories are mapped to more than one damage category as they contribute to both
  - ie. ozone layer depletion contributes to human health & ecosystem quality
- More information: http://www.sph.umich.edu/riskcenter/jolliet/impact2002+.htm

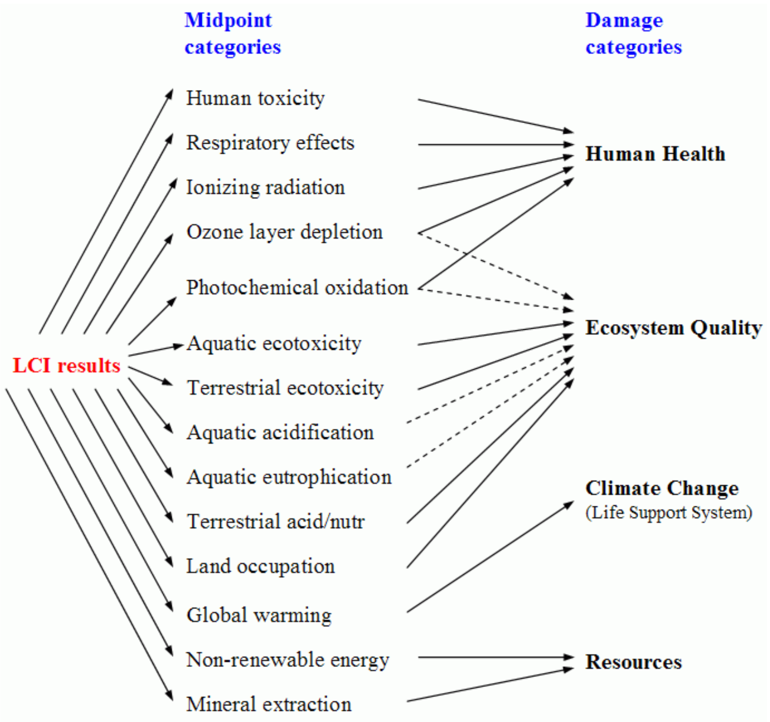


Image source: University of Michigan, http://www.sph.umich.edu/riskcenter/jolliet/impact2002+_chart.htm

ReCiPe

- Midpoint and endpoint method developed by the RIVM, CML , PRé Consultants, Radboud Universiteit Nijmegen and CE Delft
- Includes characterization and normalization
- 2008 is latest version; most recently updated midpoint & endpoint method available
- Incorporates three cultural perspectives
  - Individualist: short term, optimism that technology can avoid many problems in future
  - Hierarchist: consensus model, as often encountered in scientific models, considered to default model
  - Egalitarian: long term based on precautionary principle thinking
- More information: www.lcia-recipe.net

ReCiPe

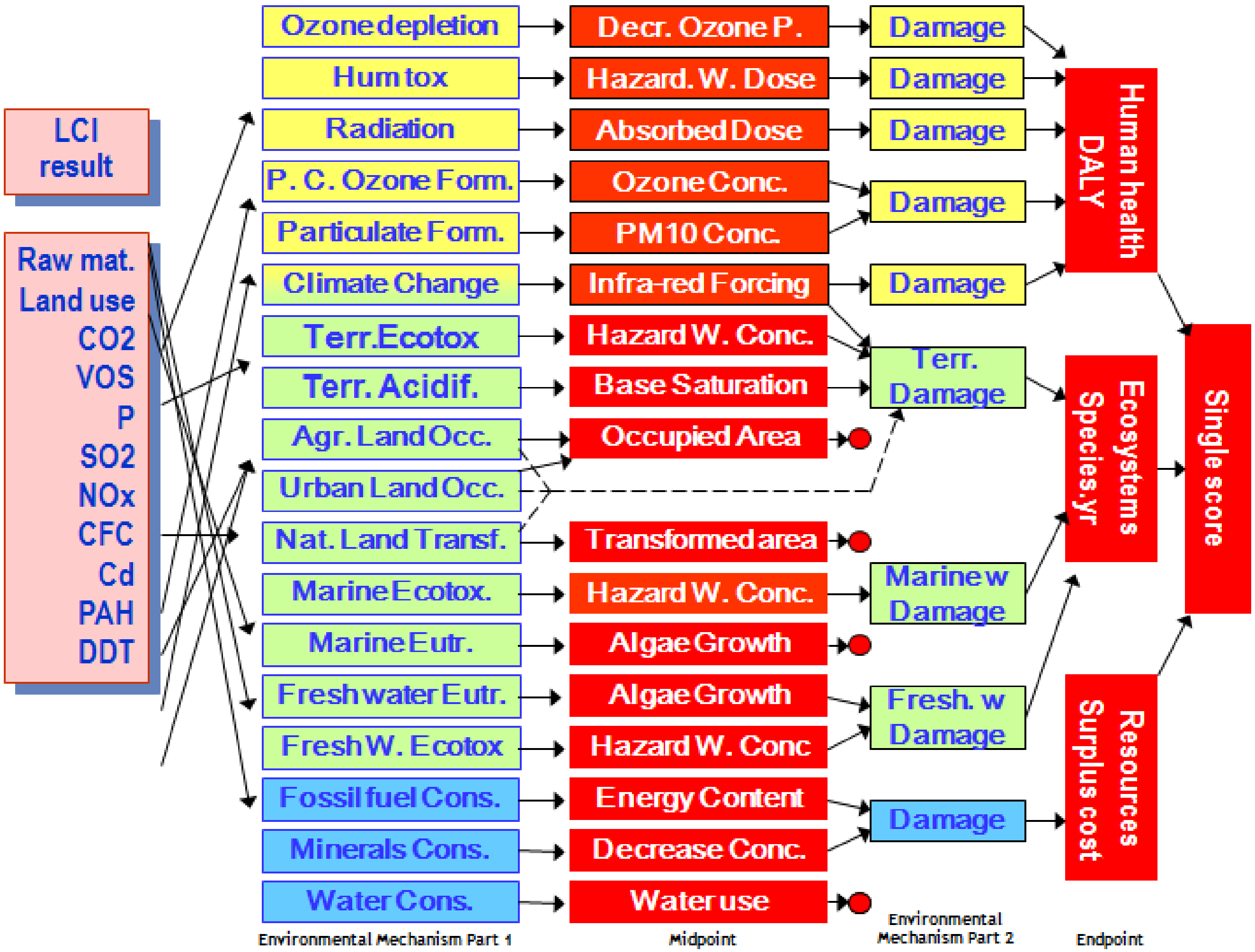


Image Source: http://www.lcia-recipe.net/

Uncertainty

- There are multiple types of uncertainty which may affect the LCA results
- Some types are controllable by the LCA practitioner to a degree
  - variability of collected data
  - life cycle model assumptions
- Other types are not
  - variability of database inventory data
  - uncertainty of impact assessment methods

Uncertainty according to ISO 14044

- Used to understand the significance, uncertainty, and sensitivity of the LCA results to
  - Help distinguish whether or not significant differences are present
  - Identify negligible results
  - Guide the life cycle impact assessment process
- Need & choice of techniques depends on accuracy & detail needed to fulfill the goal & scope of the LCA

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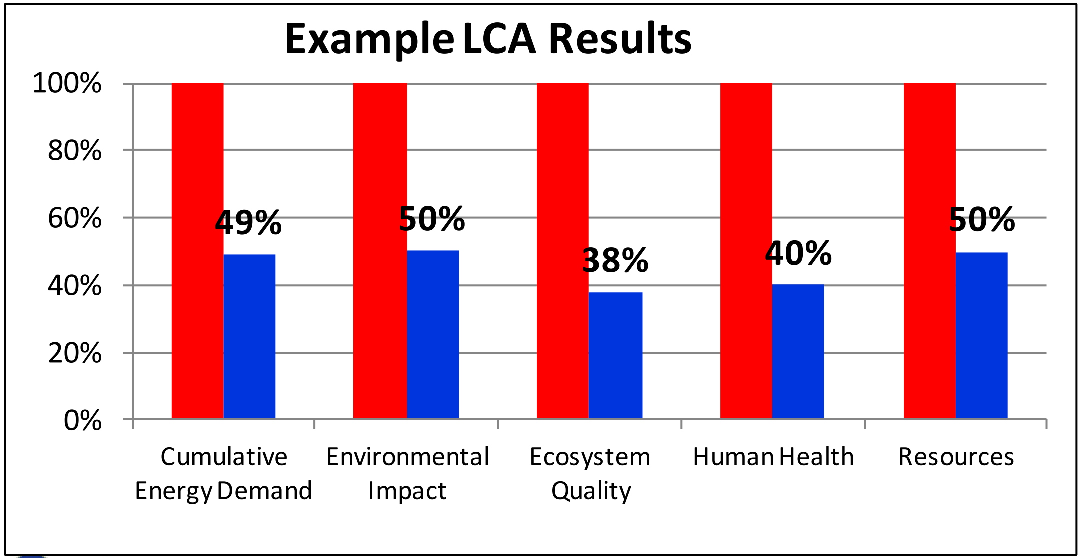
Sensitivity Analysis

- Method to estimate the effects of the LC methodology and data choices made by the LCA practitioner on the LCA results
  - Variability in collected data
  - Modeling assumptions
- Examples of data that may be tested via sensitivity analysis
  - Energy use derived from calculations
  - Variability in part weights or material types
  - Assume transport distance from manufacturer to customer
  - Assume end of life of a product
  - Impact assessment results
- May require modeling multiple scenarios

Uncertainty Analysis

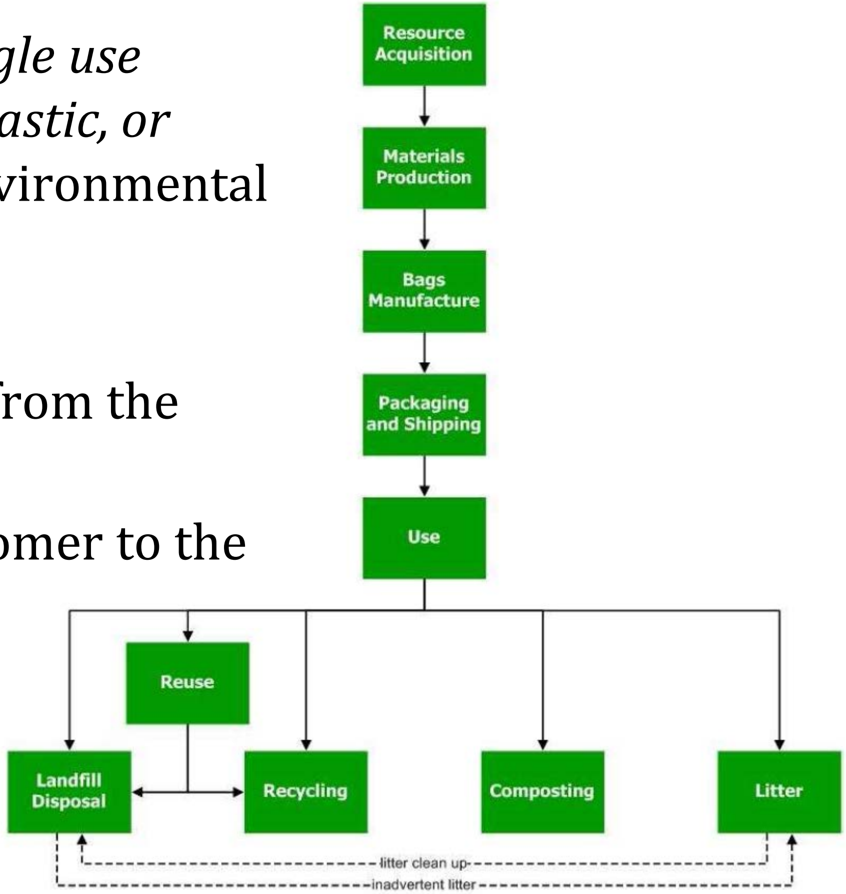
- Method to estimate how uncertainties in the impact assessment methods and life cycle inventory data available in databases may influence the results
- Estimates reliability of the results



Monte Carlo Analysis Results, 1,000 runs at 95% certainty	
Category	RED>=BLUE
Cumulative Energy Demand	0%
Environmental Impact	0.1%
Ecosystem Quality	0%
Human Health	4.8%
Resources	0%

Today's Example

- Goal:
  - Determine which grocery bag – *single use paper, single use plastic, reusable plastic, or reusable cotton* – has the lowest environmental impact
- Assumptions:
  - All bags are manufactured 100km from the customer
  - All bags travel 10km from the customer to the end of life
  - Half of paper bags are recycled at end of life, half go to landfill
  - Plastic & cotton bags go to landfill at end of life



Sustainability Victoria, Comparison of existing life cycle analysis of shopping bag alternatives, Apr07.

Functional Unit

Bag Type	Single use plastic	Single use paper	Reusable plastic	Reusable cotton
Material	HDPE	Unbleached Kraft paper	Polypropylene	Cotton
Weight	7g	42.6g	95g	85g
Relative Capacity	1	0.9	1.1	1.1
Bags per Year	520	578	4.55	4.55
Mass bags per year	3640g	24622.8g	432.25g	386.75g

Sustainability Victoria, Comparison of existing life cycle analysis of shopping bag alternatives, Apr07.

Life Cycle Inventory

Single use plastic bag to landfill

Substance	Compartment	Unit	Total	Polyethylene	Stretch blow molding	Transport, truck	Transport, municipal waste collection	Disposal, to sanitary landfill
Volume occupied, reservoir	Raw	m3day	31.46405	0.020665954	30.931745	0.36990454	0.023000912	0.118734
Water, turbine use, unspecified natural origin	Raw	Bales	439.461	0.32124675	433.52686	4.1032967	0.2596362	1.249917
Gas, natural, in ground	Raw	gal	827.9753	702.60535	122.39733	1.9104373	0.2860682	0.776144
Water, cooling, unspecified natural origin/m3	Raw	dm3	663.6833	105.3299	557.20832	0.80446372	0.099533999	0.241084
Water, river	Raw	dm3	35.94773	3.5586888	32.034812	0.23725728	0.022698411	0.094278
Water, unspecified natural origin/m3	Raw	dm3	22.00356	8.0104364	12.590744	0.4414842	0.044198903	0.916697
Gas, mine, off-gas, process, coal mining/m3	Raw	cu.in	604.2726	1.7235821	596.79262	4.4576884	0.2767618	1.021933
Water, well, in ground	Raw	cu.in	484.8047	21.550353	456.08452	5.172212	0.27703142	1.720542
Water, salt, ocean	Raw	cu.in	337.3617	29.203984	305.09966	2.1971916	0.27405056	0.586829
Wood, soft, standing	Raw	cm3	432.315	0.94287529	430.75016	0.45522437	0.033231701	0.133477

Impact Assessment - Classification

Impact category	Unit	Paper bags to Landfill & Recycling	Reusable cotton bags to landfill	Reusable plastic bags to landfill	Single use plastic bags to recycling	Single use plastic bags to incineration	Single use plastic bags to landfill
Carcinogens	kg C2H3Cl eq	0.417994	0.129259	0.153302	1.231264	1.177576	1.127107
Non-carcinogens	kg C2H3Cl eq	0.740271	0.463388	0.004723	0.117981	0.350686	0.067419
Respiratory inorganics	kg PM2.5 eq	0.037581	0.013779	0.000555	0.00514	0.007426	0.007284
Ionizing radiation	Bq C-14 eq	1035.931	116.8382	13.49738	417.1185	418.0241	417.9823
Ozone layer depletion	kg CFC-11 eq	3.08E-06	2.01E-07	1.92E-08	-1.3E-06	3.08E-07	3.14E-07
Respiratory organics	kg C2H4 eq	0.015228	0.000859	0.001044	-0.01999	0.010705	0.010603
Aquatic ecotoxicity	kg TEG water	-584.219	510.5823	16.15509	7983.769	342.6306	305.4632
Terrestrial ecotoxicity	kg TEG soil	743.9329	249.3385	3.348683	59.85814	56.73934	56.83179
Terrestrial acid/nutri	kg SO2 eq	0.730762	0.326098	0.013255	0.042056	0.162103	0.15584
Land occupation	m2org.arable	25.89123	4.233037	0.009774	0.114647	0.115059	0.120109
Aquatic acidification	kg SO2 eq	0.16954	0.094797	0.00373	0.041507	0.048866	0.048261
Aquatic eutrophication	kg PO4 P-lim	0.004834	0.003622	6.61E-05	0.000225	0.000172	0.000181
Global warming	kg CO2 eq	22.34385	9.056268	1.034412	10.45722	22.57957	11.87871
Non-renewable energy	MJ primary	331.84	106.9904	37.45004	278.1647	391.6313	391.9828
Mineral extraction	MJ surplus	0.429864	0.049432	0.003704	0.038234	0.040382	0.039691

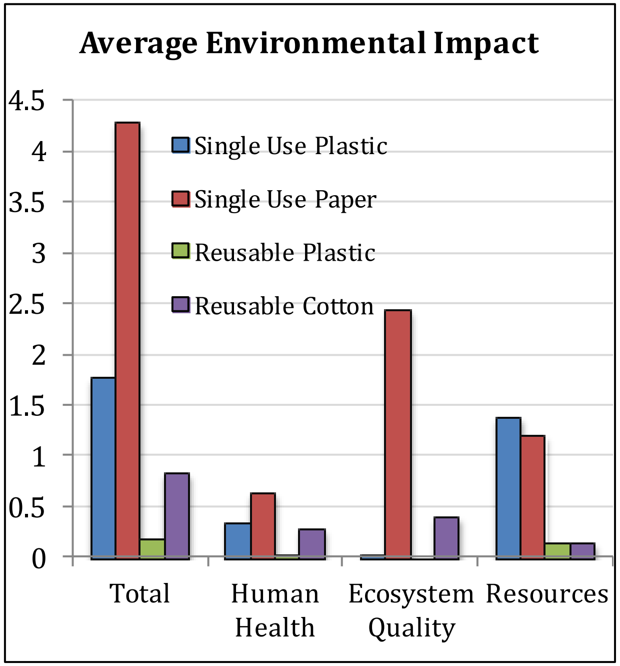
Impact Assessment - Characterization

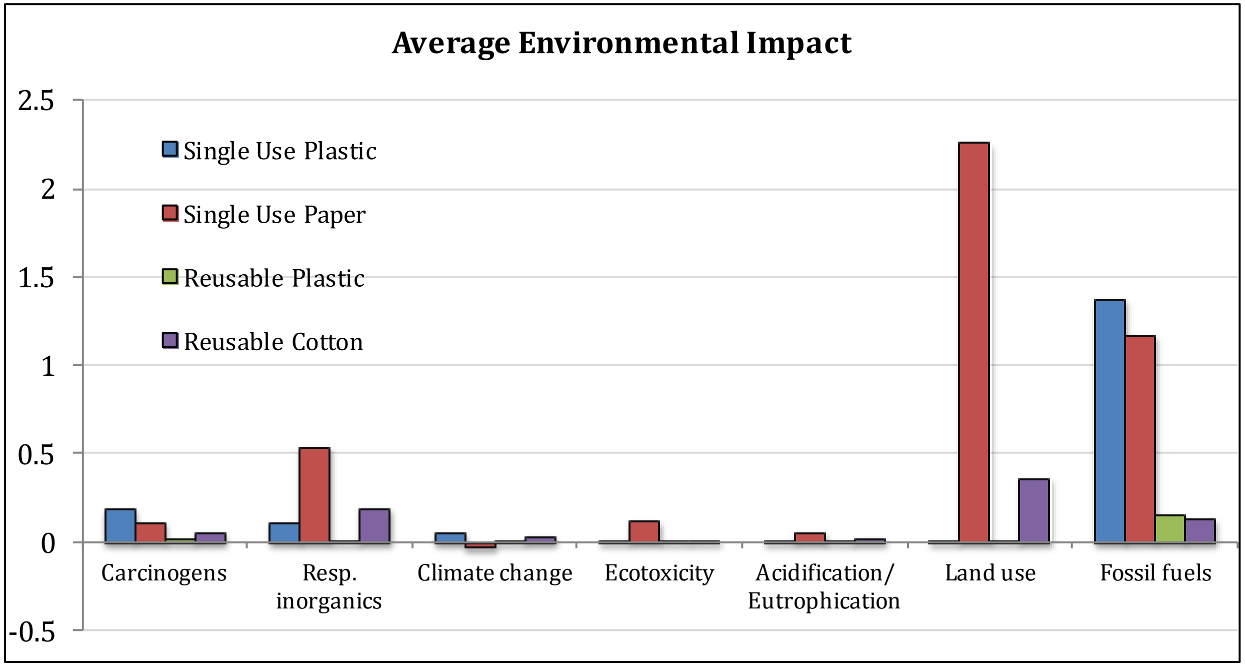
Impact category	Unit	Paper bags to Landfill & Recycling	Reusable cotton bags to landfill	Reusable plastic bags to landfill	Single use plastic bags to recycling	Single use plastic bags to incineration	Single use plastic bags to landfill
Carcinogens	DALY	1.17E-06	3.62E-07	4.29E-07	3.45E-06	3.3E-06	3.16E-06
Non-carcinogens	DALY	2.07E-06	1.3E-06	1.32E-08	3.3E-07	9.82E-07	1.89E-07
Respiratory inorganics	DALY	2.63E-05	9.65E-06	3.88E-07	3.6E-06	5.2E-06	5.1E-06
Ionizing radiation	DALY	2.18E-07	2.45E-08	2.83E-09	8.76E-08	8.78E-08	8.78E-08
Ozone layer depletion	DALY	3.24E-09	2.11E-10	2.02E-11	-1.4E-09	3.24E-10	3.29E-10
Respiratory organics	DALY	3.24E-08	1.83E-09	2.22E-09	-4.3E-08	2.28E-08	2.26E-08
Aquatic ecotoxicity	PDF*m2*yr	-0.02933	0.025631	0.000811	0.400785	0.0172	0.015334
Terrestrial ecotoxicity	PDF*m2*yr	5.884509	1.972268	0.026488	0.473478	0.448808	0.449539
Terrestrial acid/nutri	PDF*m2*yr	0.759993	0.339142	0.013786	0.043739	0.168587	0.162074
Land occupation	PDF*m2*yr	28.22144	4.61401	0.010654	0.124965	0.125415	0.130919
Aquatic acidification		-	-	-	-	-	-
Aquatic eutrophication		-	-	-	-	-	-
Global warming	kg CO2 eq	22.34385	9.056268	1.034412	10.45722	22.57957	11.87871
Non-renewable energy	MJ primary	331.84	106.9904	37.45004	278.1647	391.6313	391.9828
Mineral extraction	MJ primary	0.429864	0.049432	0.003704	0.038234	0.040382	0.039691

Impact Assessment – Normalized & Weighted

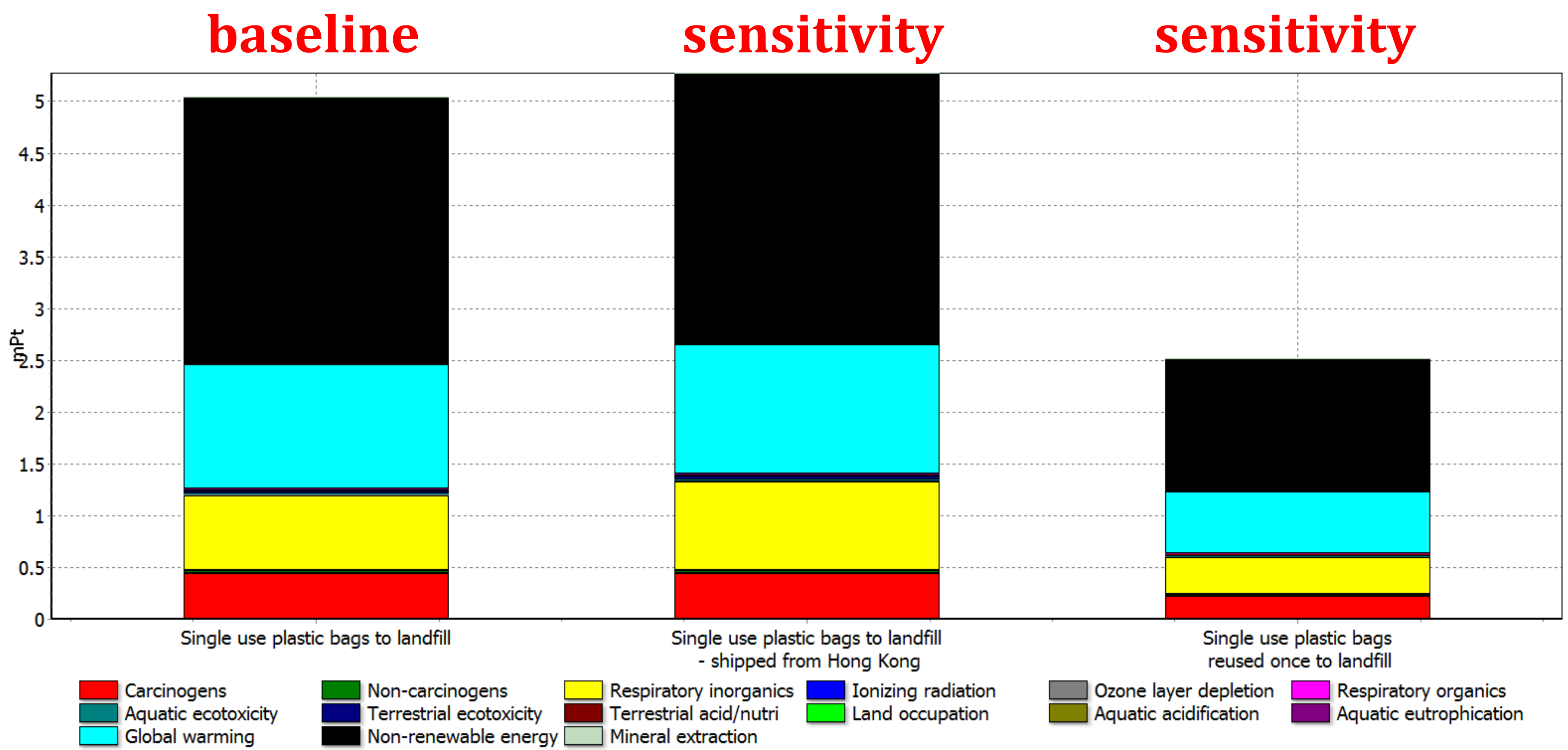
Impact category	Unit	Paper bags to Landfill & Recycling	Reusable cotton bags to landfill	Reusable plastic bags to landfill	Single use plastic bags to recycling	Single use plastic bags to incineration	Single use plastic bags to landfill
Total	Pt	0.011188	0.003724	0.000473	0.004009	0.006265	0.005041
Carcinogens	Pt	0.000165	5.1E-05	6.05E-05	0.000486	0.000465	0.000445
Non-carcinogens	Pt	0.000292	0.000183	1.86E-06	4.66E-05	0.000138	2.66E-05
Respiratory inorganics	Pt	0.003709	0.00136	5.47E-05	0.000507	0.000733	0.000719
Ionizing radiation	Pt	3.07E-05	3.46E-06	4E-07	1.24E-05	1.24E-05	1.24E-05
Ozone layer depletion	Pt	4.56E-07	2.98E-08	2.84E-09	-2E-07	4.56E-08	4.64E-08
Respiratory organics	Pt	4.57E-06	2.58E-07	3.14E-07	-6E-06	3.21E-06	3.18E-06
Aquatic ecotoxicity	Pt	-2.1E-06	1.87E-06	5.92E-08	2.93E-05	1.26E-06	1.12E-06
Terrestrial ecotoxicity	Pt	0.00043	0.000144	1.93E-06	3.46E-05	3.28E-05	3.28E-05
Terrestrial acid/nutri	Pt	5.55E-05	2.48E-05	1.01E-06	3.19E-06	1.23E-05	1.18E-05
Land occupation	Pt	0.00206	0.000337	7.78E-07	9.12E-06	9.16E-06	9.56E-06
Aquatic acidification	Pt	-	-	-	-	-	-
Aquatic eutrophication	Pt	-	-	-	-	-	-
Global warming	Pt	0.002257	0.000915	0.000104	0.001056	0.002281	0.0012
Non-renewable energy	Pt	0.002184	0.000704	0.000246	0.00183	0.002577	0.002579
Mineral extraction	Pt	2.83E-06	3.25E-07	2.44E-08	2.52E-07	2.66E-07	2.61E-07

LCA Results - Product Comparison



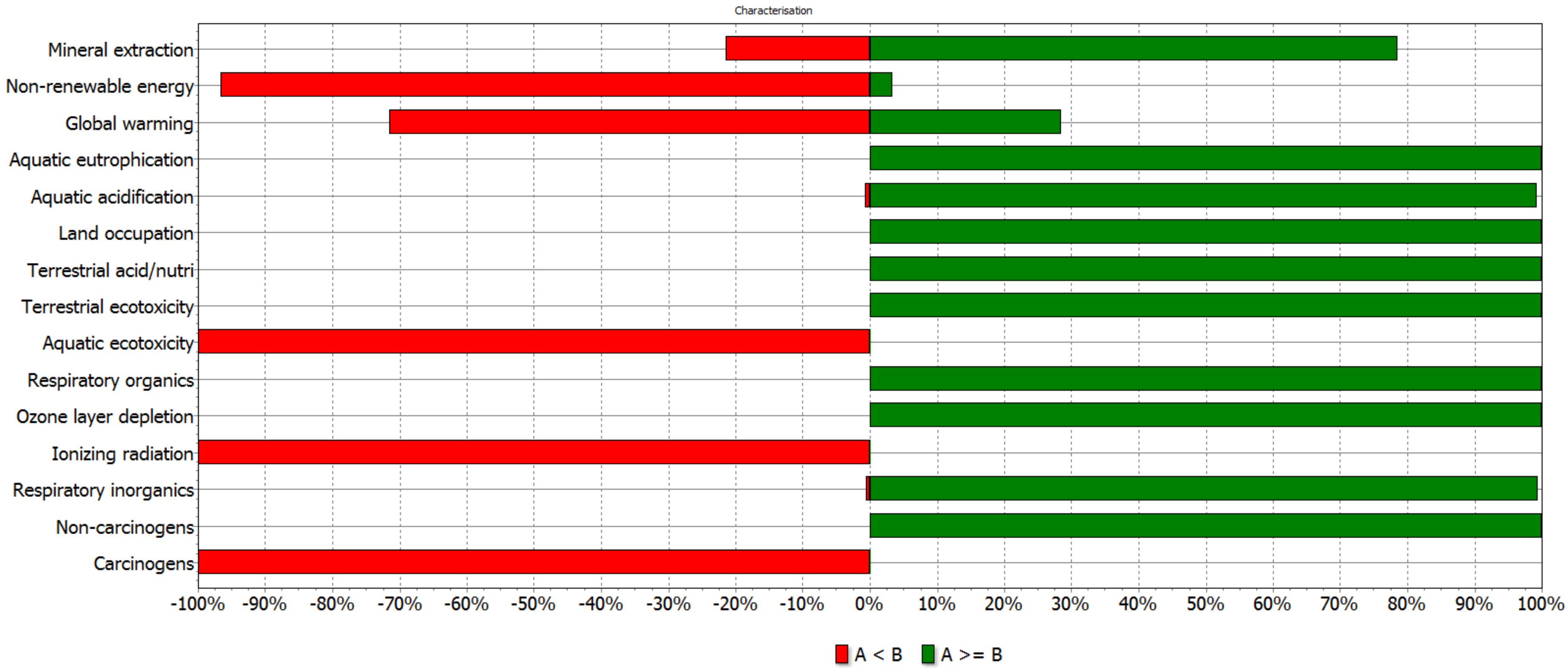


Sensitivity Analysis



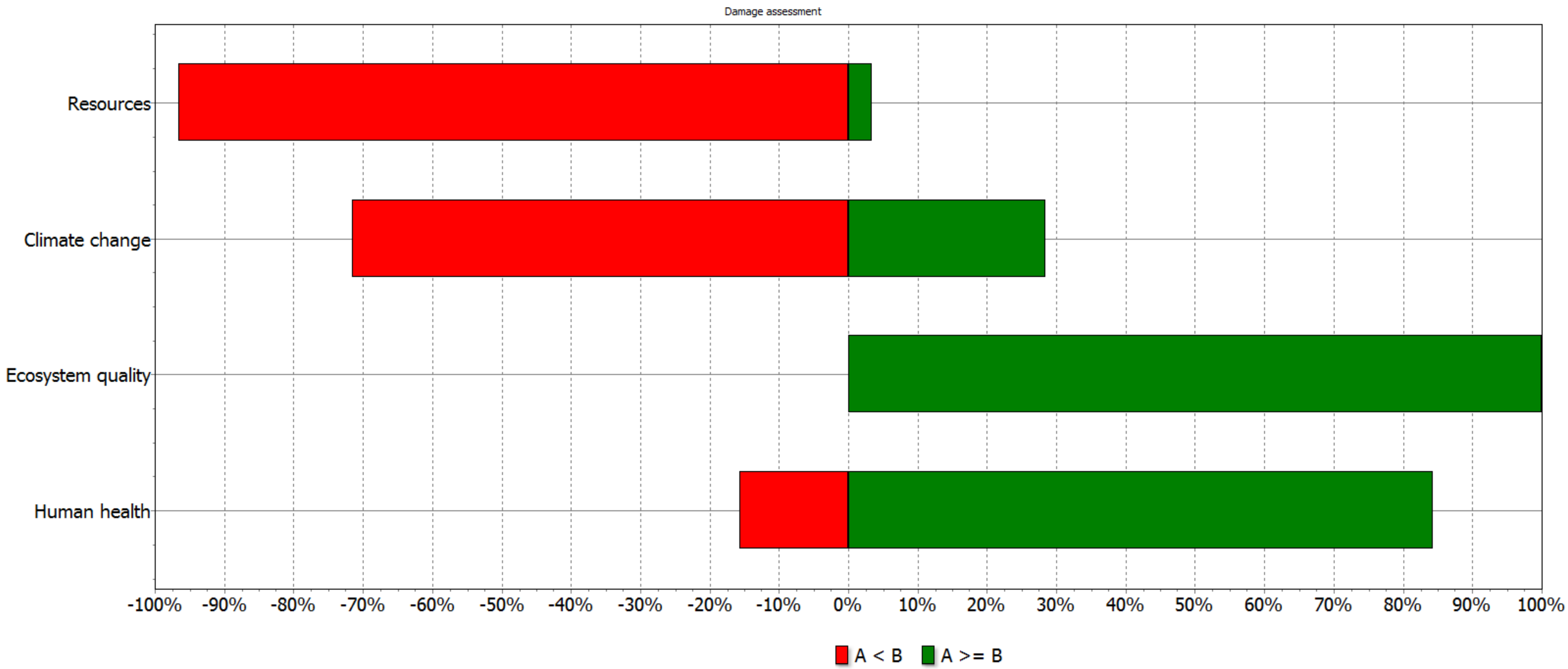
Comparing 1 p 'Single use plastic bags to landfill', 1 p 'Single use plastic bags to landfill - shipped from Hong Kong to CA' and 1 p 'Single use plastic bags reused once to landfill'; Method: IMPACT 2002+ V2.05 / IMPACT 2002+ / Single score

Monte Carlo Analysis



Uncertainty analysis of 1 p 'Reusable cotton bags to landfill' (A) minus
1 p 'Single use plastic bags to recycling' (B),
method: IMPACT 2002+ V2.05 / IMPACT 2002+ , confidence interval: 95 %

Monte Carlo Analysis



Uncertainty analysis of 1 p 'Reusable cotton bags to landfill' (A) minus
1 p 'Single use plastic bags to recycling' (B),
method: IMPACT 2002+ V2.05 / IMPACT 2002+ , confidence interval: 95 %

Summary

- Scoping is Critical: Well-defined LCA goals and boundary selection is very important
  - Will affect the Impact categories, category indicators, characterization models, use of normalization and weighting
- Critical to consider variability of input data: sensitivity analyses are necessary for testing
- Use Monte Carlo analysis to improve confidence in the LCA results

Questions & Discussion

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