Tools to Measure Sustainability:
Life Cycle Assessment

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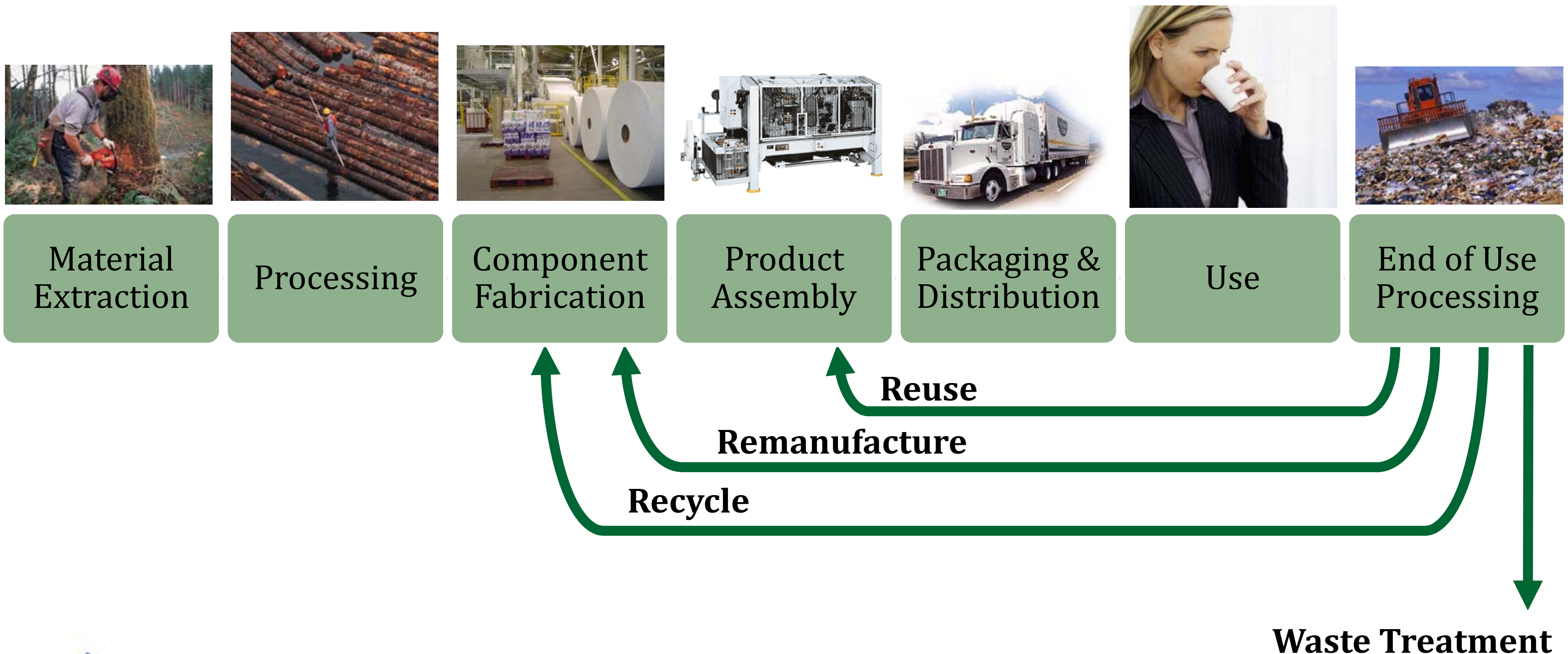
Life Cycle Assessment

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.

Benefits of LCA

- **Quantify environmental benefits** of products
- Provide **credible evidence** for marketing claims
- Identify opportunities to **improve the environmental performance** of products at various points in their life cycle
- **Inform decision-makers** in industry, government or non-governmental organizations
- Select **relevant indicators** of environmental performance, including measurement techniques
- Validate product **marketing claims**
- **Instill life cycle thinking** within businesses

Methods of Conducting LCA

(1) Manual
(2) Software
(3) Consultant

- Advantages of product/process analysis over life-cycle vs. analysis of 1 stage of LCA (ie – manufacturing)

Step 1: Goal Definition and Scoping

Define the **goal**:

- Intended application of the study
- Intended audience

Define the **scope**:

- Identify the product system to be studied
- Define the functional unit
- Define the boundaries of the product system
- Identify assumptions and limitations of the study
- Select impact categories to be included

Step 2: Life cycle inventory

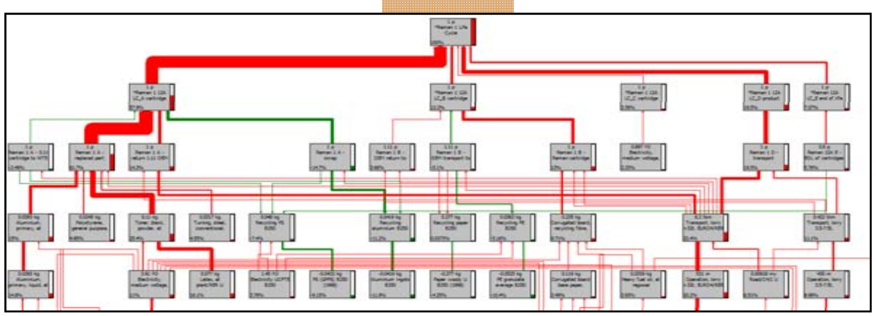
Inventory collected from multiple sources

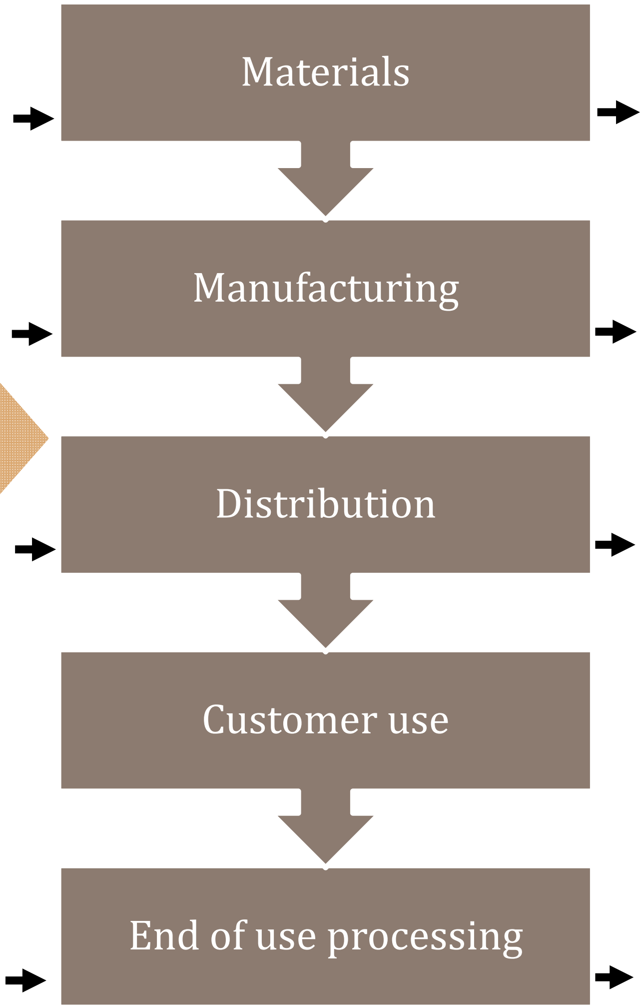
Inputs

Energy

Raw Materials

ecoinvent data





Outputs

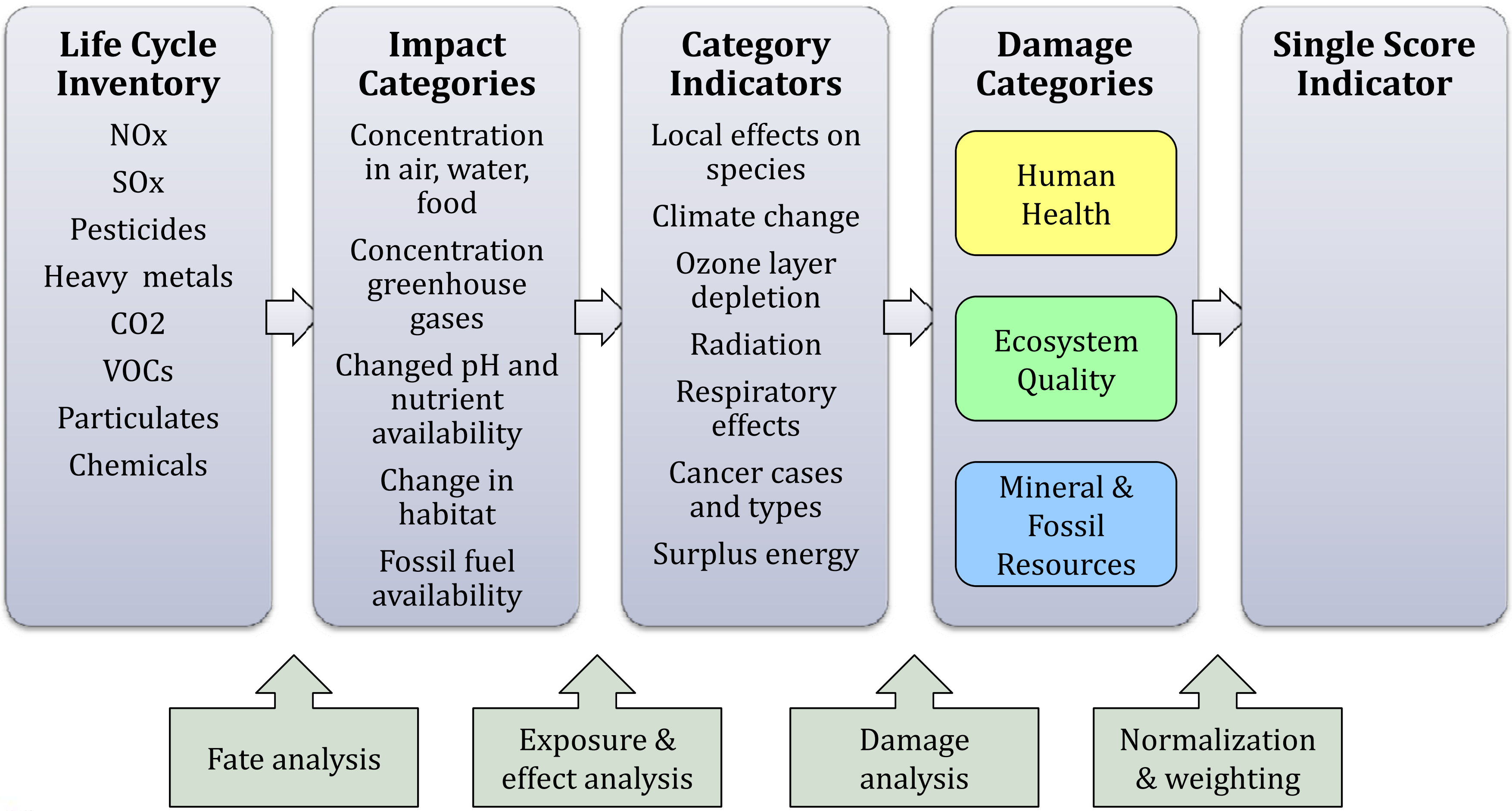
Products

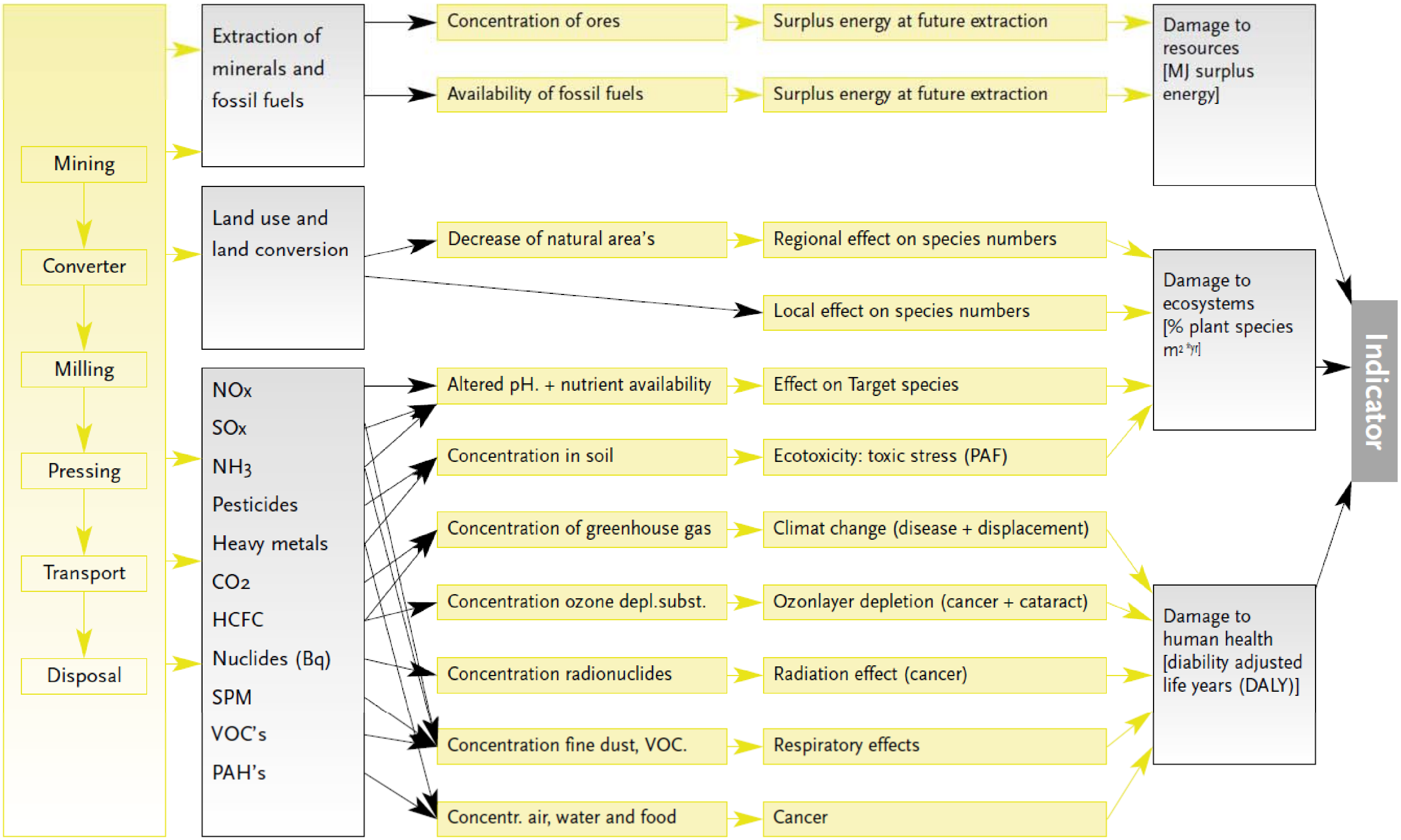
Air, Water and Solid Emissions

Step 3: Impact Assessment

- Converts the inventory into impact categories or end points which explain the environmental effect
- Impact categories 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

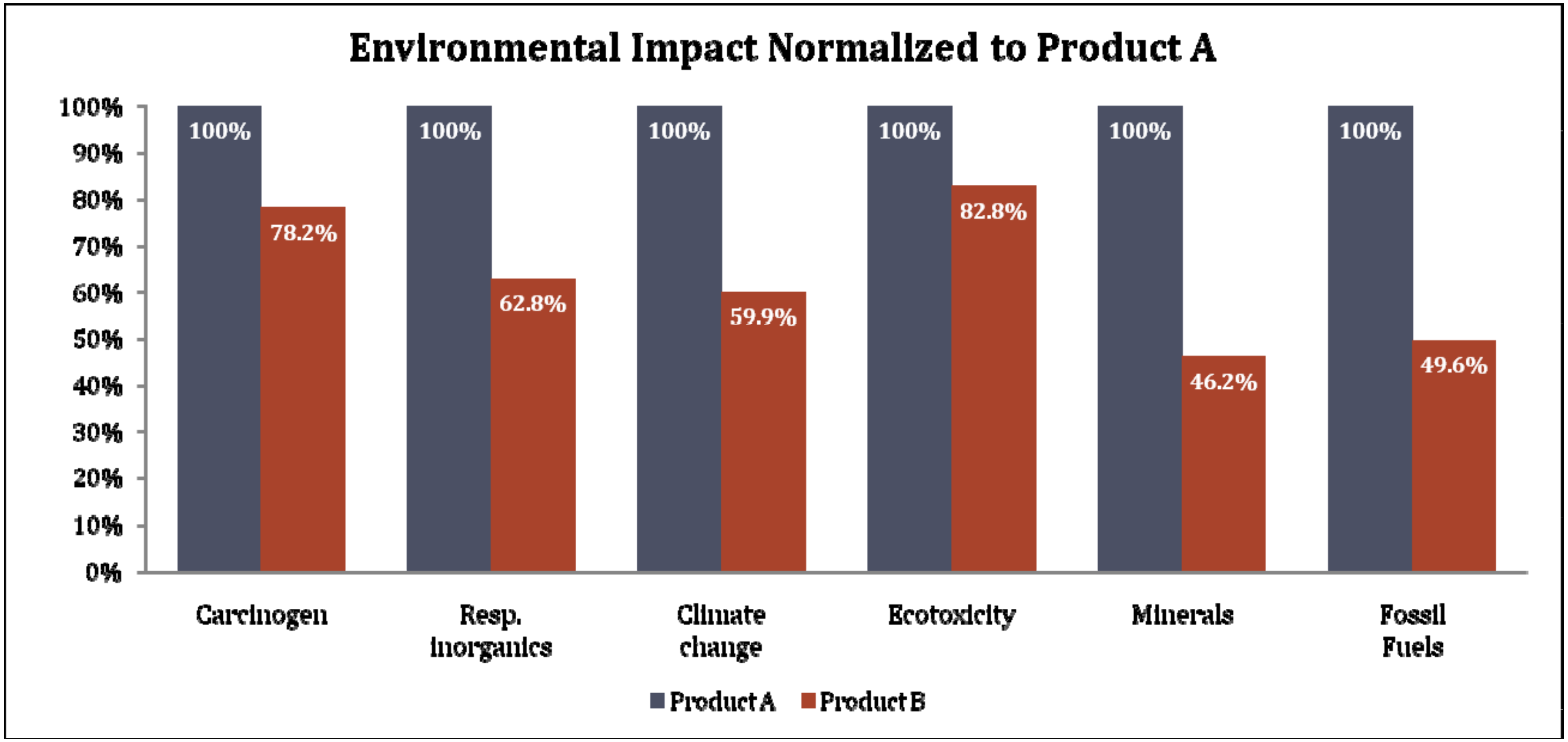




Eco-Indicator 99 Manual for Designers, Ministry of Housing, Spatial Planning, and the Environment, The Netherlands, Oct2000.

Impact Assessment Results

- Impact assessment converts the inventory into impact categories or end points which details the human health and environmental effects.



Step 4: Report Results

- Life cycle interpretation: findings of the inventory analysis or impact assessment are evaluated in relation to the goal and scope of the study to reach conclusions and recommendations

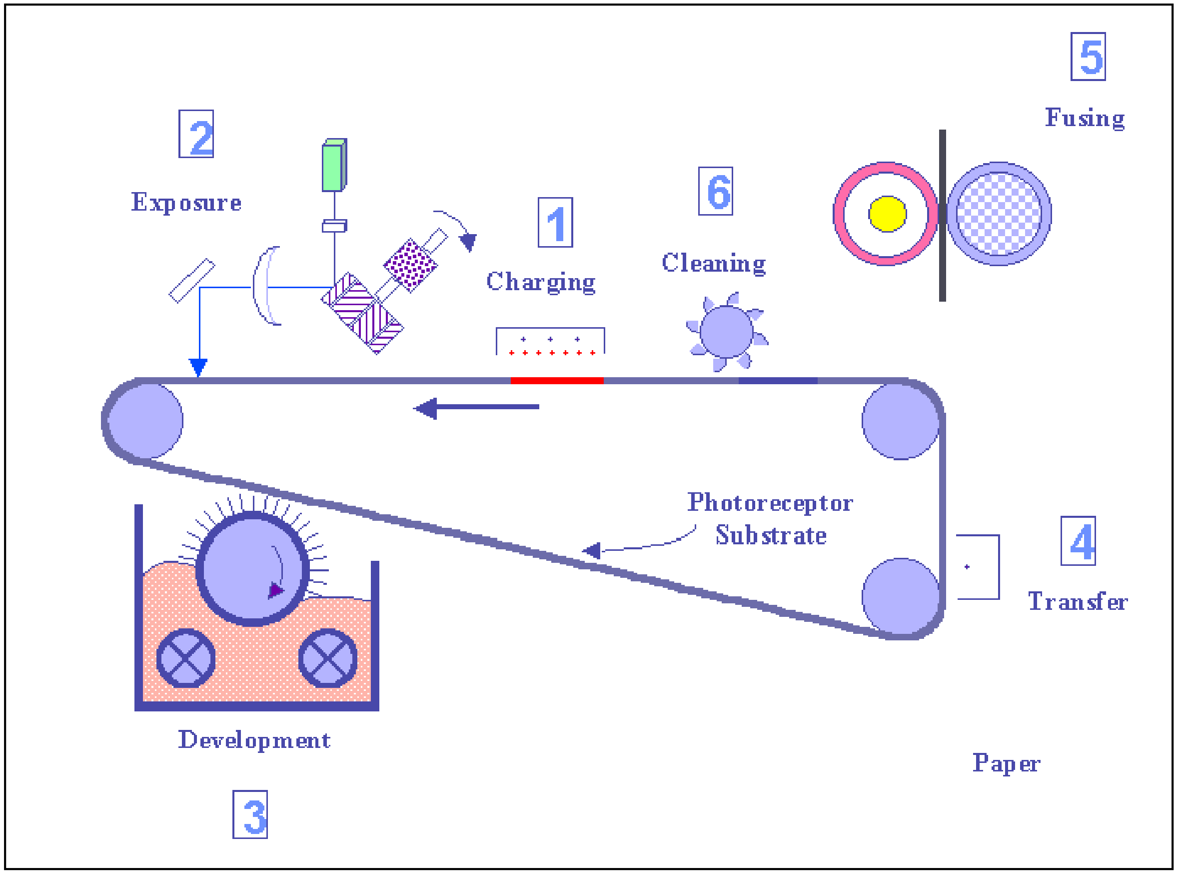
1. Identify significant issues
2. Evaluate results for completeness, consistency, and sensitivity of the data
3. Draw conclusions & make recommendations consistent with the goal & scope of the study

Manual Calculations

Manual Calculations

- Example of Life Cycle Inventory (LCI): Toner
  - Published in Journal of Cleaner Production, 2003
- Highly data intensive
- Detailed mass & energy balances performed over life-cycle
- Advantages: measure data & define baseline metrics of manufacturing process
- Challenges: Assumptions made when data unavailable

Xerography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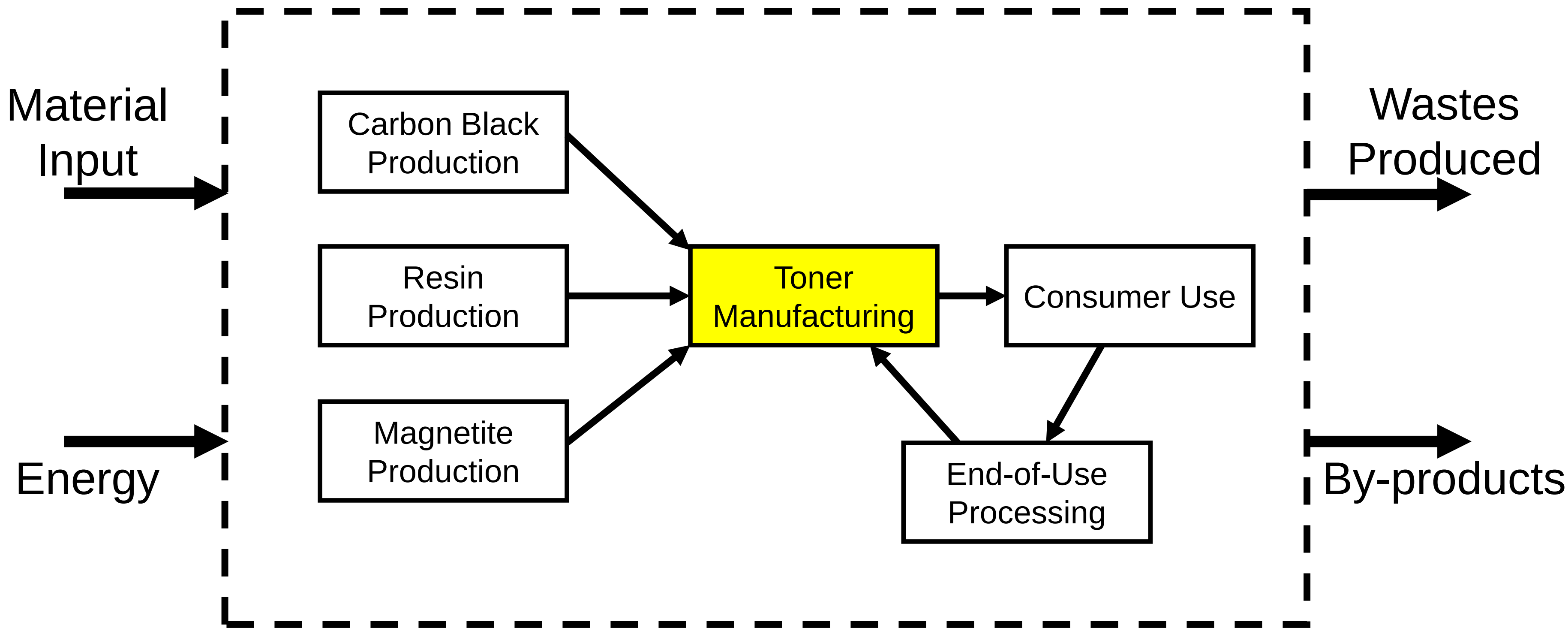
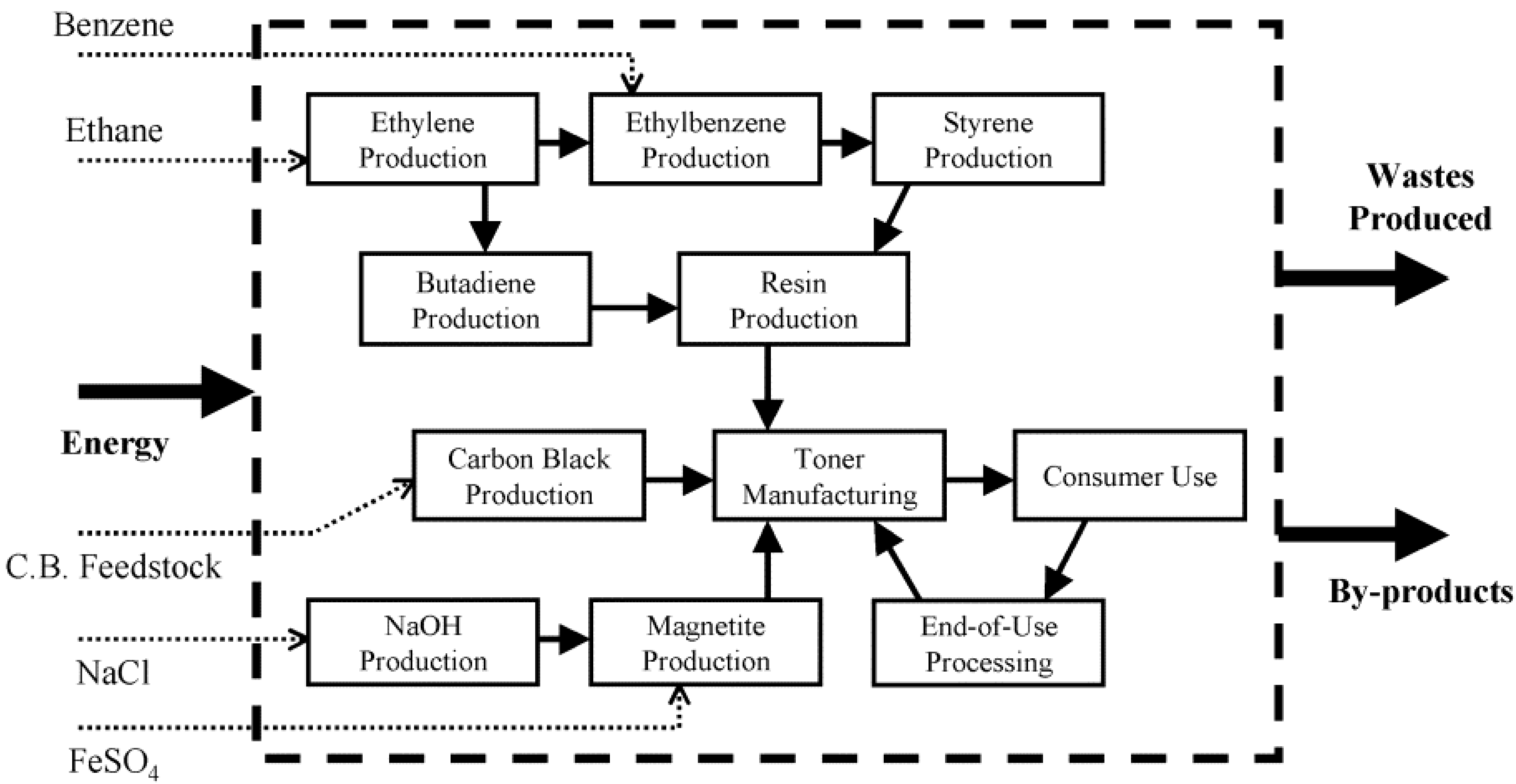
Fusing
2
Exposure
1
Charging
6
Cleaning
Photoreceptor
Substrate
4
Transfer
Development
Paper
3

Defining the Boundaries



Ref: A.Ahmadi,et.al, J.Clean.Prod., 2003

Toner Life-cycle Inventory



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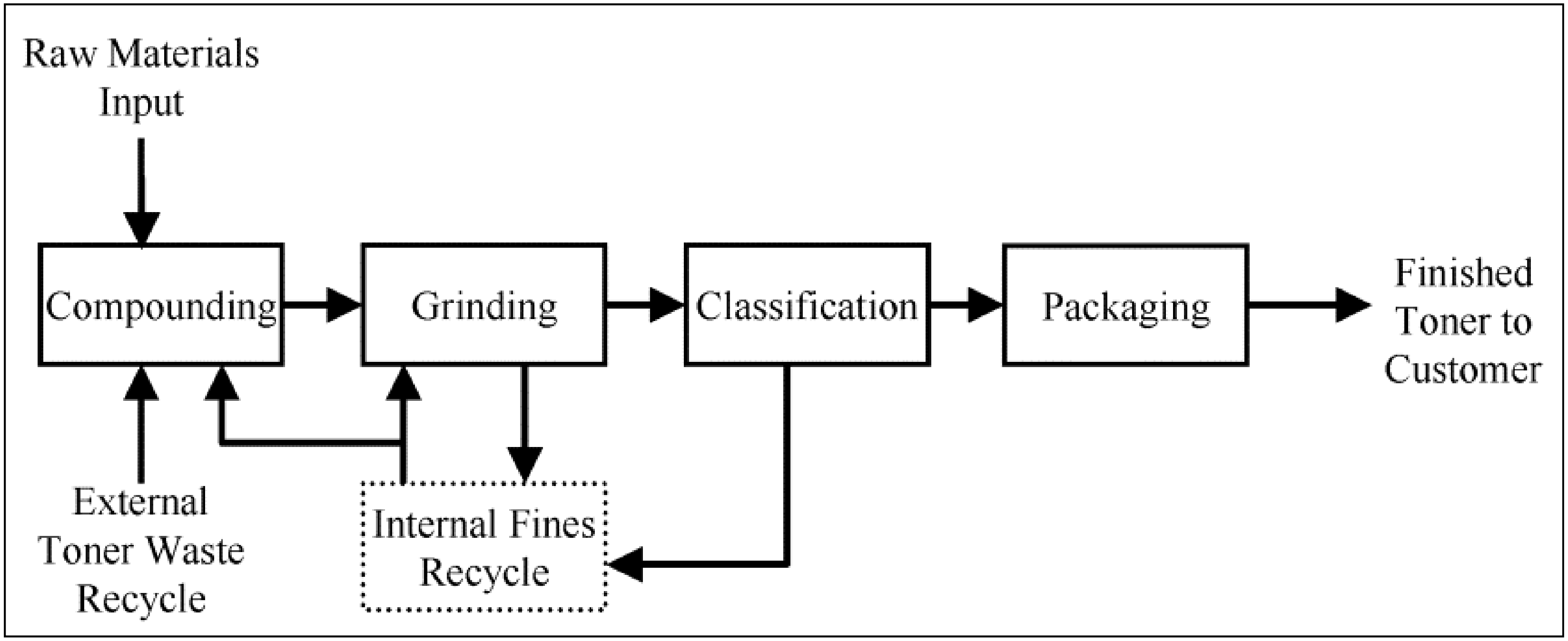
Toner Manufacturing Process



Functional Unit = 1 metric tonne of toner produced

Two Key Recycling Loops: Internal/External

Ref: A.Ahmadi,et.al, J.Clean.Prod., 2003

Results

	Energy Use	Fossil Fuel	Electricity	CO_2	NO_x	SO_2	VOC's	Particulates	Wastewater	Solid Waste
Units	10^6 kJ	10^6 kJ	10^6 kJ	10^3 kg	kg	kg	kg	kg	m^3	kg
Carbon Black Production										
Magnatite Production										
NaOH										
Magnatite										
Resin Production										
Ethane S.C.										
Ethylbenzene										
Styrene										
Butadiene										
Resin										
Toner Manufacturing	22	min	22	1.4	6.2	12	1.3	4.9	min	23
Consumer Use										
End of Use Processing										
Toner Recycle										
De-inking of Paper										
Toner on Paper to Landfill										
Transportation										
Raw Materials to T. Man.										
Toner to Customer										
Toner Waste Recycle										
Total	22	min	22	1.4	6.2	12	1.3	4.9	min	23

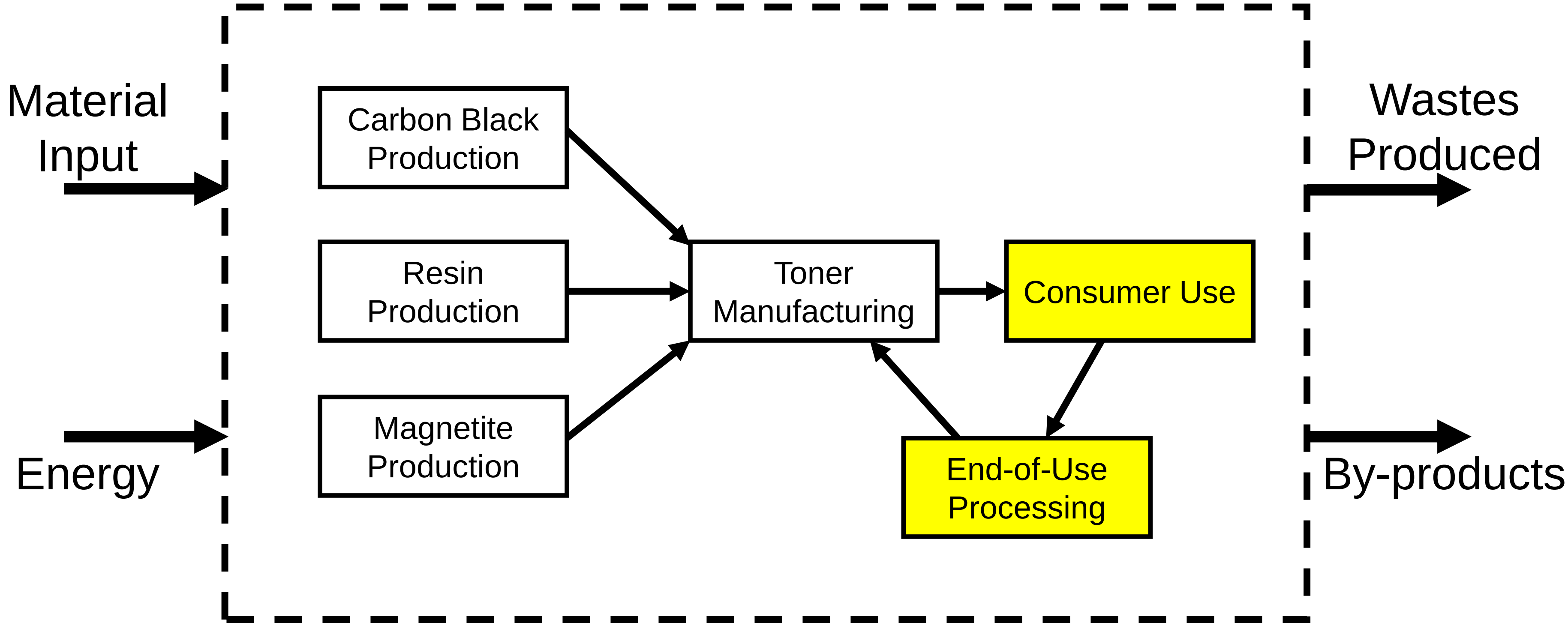
Ref: A.Ahmadi,et.al, J.Clean.Prod., 2003

Results

	Energy Use	Fossil Fuel	Electricity	CO_2	NO_x	SO_2	VOC's	Particulates	Wastewater	Solid Waste
Units	10^6 kJ	10^6 kJ	10^6 kJ	10^3 kg	kg	kg	kg	kg	m^3	kg
Carbon Black Production										
Magnatite Production										
NaOH										
Magnatite										
Resin Production	**4.7**	**4.0**	**0.7**	**0.25**	**0.71**	**0.4**	**22.1**	**0.17**	**1.0**	**14**
Ethane S.C.	1.4	1.4	min	0.07	0.18	0.0	1.2	min	min	min
Ethylbenzene	0.7	0.66	min	0.03	0.09	0.0	7.2	min	min	min
Styrene	1.8	1.8	min	0.10	0.24	0.0	6.5	min	min	min
Butadiene	0.1	min	0.1	0.01	0.02	0.0	0.61	0.02	min	min
Resin	0.7	0.11	0.6	0.04	0.19	0.3	6.6	0.15	1.0	14
Toner Manufacturing	**22**	**min**	**22**	**1.4**	**6.2**	**12**	**1.3**	**4.9**	**min**	**23**
Consumer Use										
End of Use Processing										
Toner Recycle										
De-inking of Paper										
Toner on Paper to Landfill										
Transportation										
Raw Materials to T. Man.										
Toner to Customer										
Toner Waste Recycle										
Total	**27**	**4.0**	**23**	**1.6**	**6.9**	**12**	**23**	**5.1**	**1.0**	**37**

Ref: A.Ahmadi,et.al, J.Clean.Prod., 2003

The System



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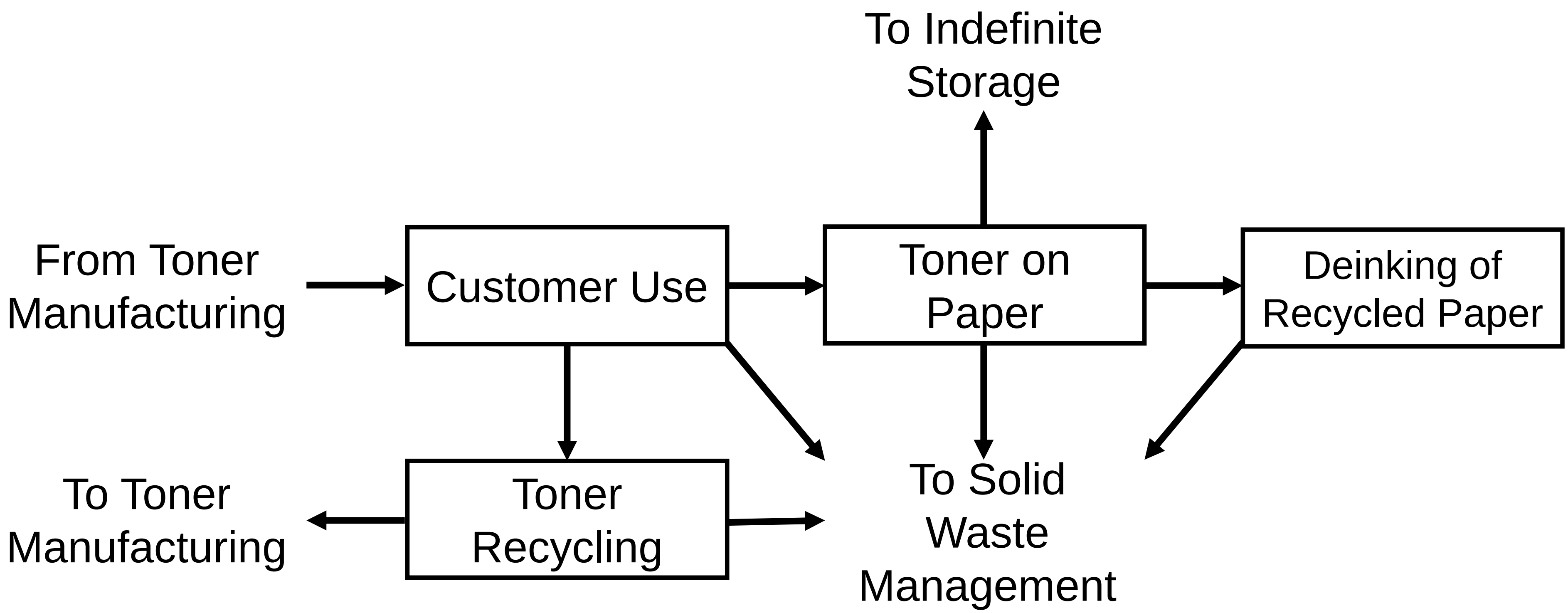
Post-production Processing

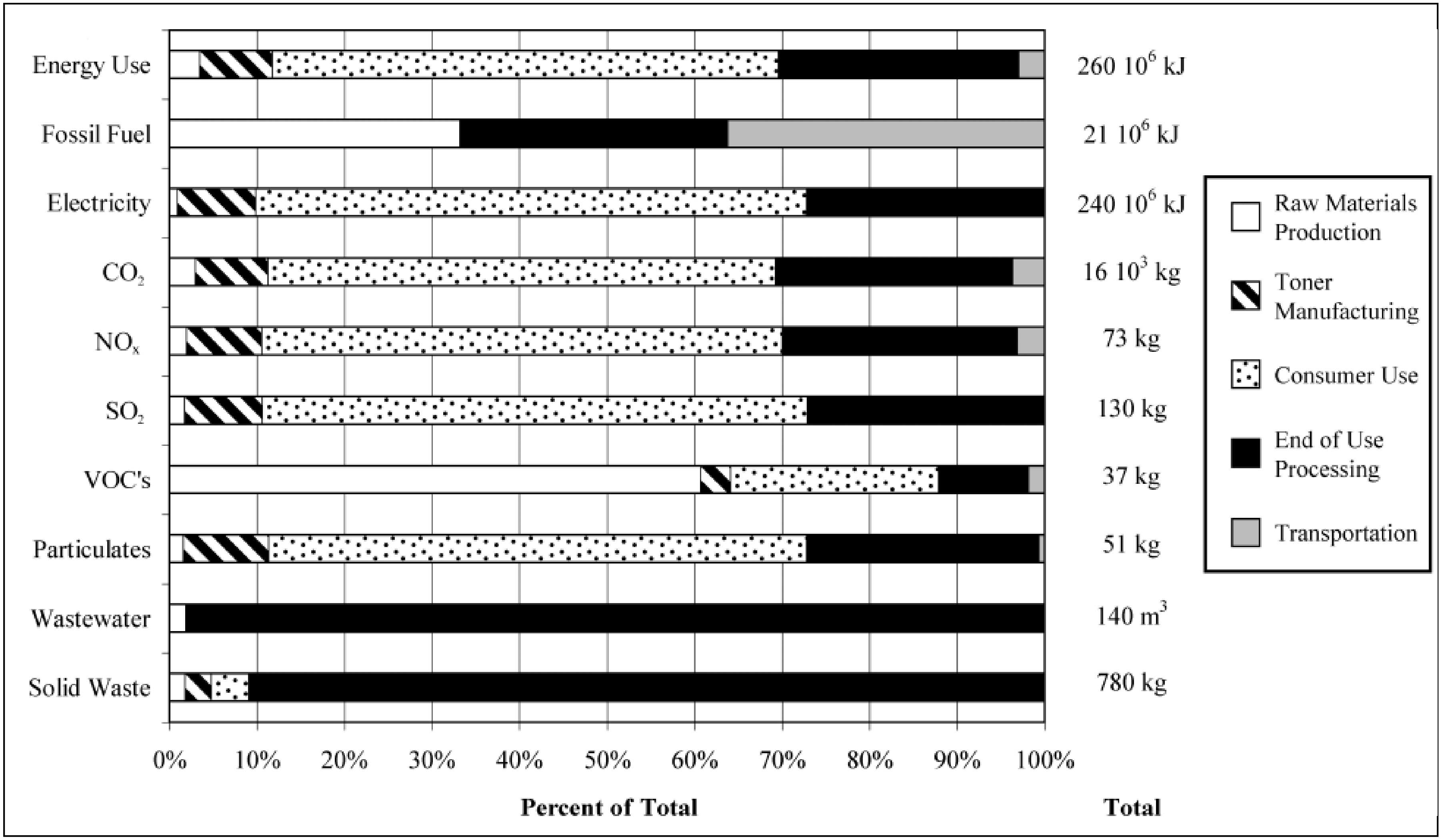


- Post production processes begin once the toner is sent to the customer and include:
  - Use of the toner in the xerographic machines
  - Destination of waste toner left in the machines
  - Final destination of the toner that is transferred to the paper

Results

	Energy Use	Fossil Fuel	Electricity	CO_2	NO_x	SO_2	VOC's	Particulates	Wastewater	Solid Waste
Units	10^6 kJ	10^6 kJ	10^6 kJ	10^3 kg	kg	kg	kg	kg	m^3	kg
Carbon Black Production	**1.5**	**1.5**	**min**	**0.06**	**0.12**	**1.1**	**0.10**	**0.07**	**min**	**min**
Magnatite Production	**2.9**	**1.6**	**1.4**	**0.17**	**0.59**	**0.7**	**0.08**	**0.56**	**1.5**	**min**
NaOH	1.2	0.1	1.1	0.08	0.33	0.6	0.06	0.23	min	min
Magnatite	1.7	1.4	0.3	0.09	0.26	0.1	0.02	0.34	1.5	min
Resin Production	**4.7**	**4.0**	**0.7**	**0.25**	**0.71**	**0.4**	**22.1**	**0.17**	**1.0**	**14**
Ethane S.C.	1.4	1.4	min	0.07	0.18	0.0	1.2	min	min	min
Ethylbenzene	0.7	0.66	min	0.03	0.09	0.0	7.2	min	min	min
Styrene	1.8	1.8	min	0.10	0.24	0.0	6.5	min	min	min
Butadiene	0.1	min	0.1	0.01	0.02	0.0	0.61	0.02	min	min
Resin	0.7	0.11	0.6	0.04	0.19	0.3	6.6	0.15	1.0	14
Toner Manufacturing	**22**	**min**	**22**	**1.4**	**6.2**	**12**	**1.3**	**4.9**	**min**	**23**
Consumer Use	**150**	**min**	**150**	**9.5**	**43**	**82**	**8.7**	**31**	**min**	**34**
End of Use Processing	**72**	**6.5**	**65**	**4.4**	**20**	**35**	**3.8**	**13**	**140**	**710**
Toner Recycle	min	min	min	min	min	min	min	min	min	9.2
De-inking of Paper	72	6.5	65	4.4	20	35	3.8	13	140	390
Toner on Paper to Landfill	min	min	min	min	min	min	min	min	min	320
Transportation	**7.6**	**7.6**	**min**	**0.60**	**2.3**	**0.1**	**0.68**	**0.33**	**min**	**min**
Raw Materials to T. Man.	3.4	3.4	min	0.27	1.0	0.0	0.31	0.15	min	min
Toner to Customer	2.6	2.6	min	0.19	0.73	0.0	0.22	0.11	min	min
Toner Waste Recycle	1.6	1.6	min	0.13	0.49	0.0	0.15	0.07	min	min
Total	**260**	**21**	**240**	**16**	**73**	**130**	**37**	**51**	**140**	**780**

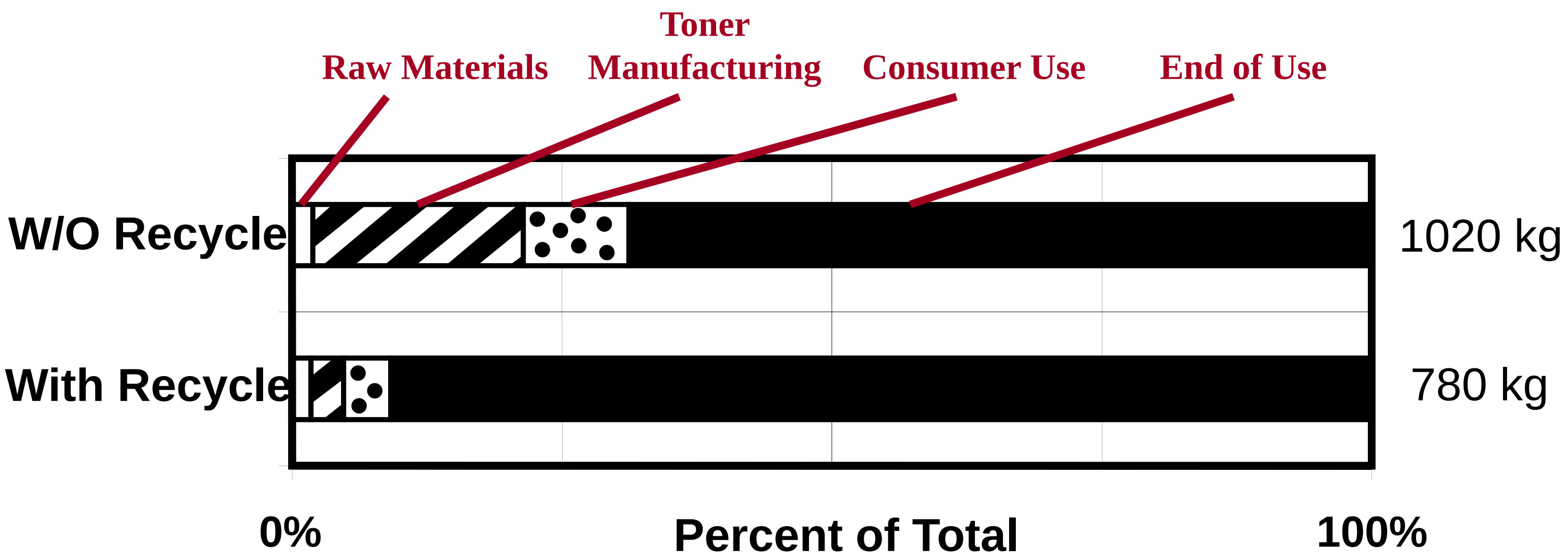
Toner Life-cycle Inventory



Ref: A.Ahmadi,et.al, J.Clean.Prod., 2003

Toner Life-cycle Inventory

Waste/Materials	Without Recycling (kg/mton)	With Recycling (kg/mton)	Percent Reduction
Solid Waste Produced in the Life-cycle	1020	780	24%
Virgin Materials Used in Toner Life-cycle	2530	1790	29%



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Software Calculations

Software Calculations

- Ability to translate the inventory data to environmental impact
- Used to facilitate life cycle assessments
- Useful for relatively quick comparisons or complex studies
- Process
  - User collects input and output data
  - Imbedded inventories populate the associate energy, materials, and wastes associated with materials and processes
  - Impact assessment translates the inventory to environmental damage
- Two ways to input data:
  1. Actual data can be input
  2. Select data from the imbedded database
- SimaPro commercially available software - http://www.pre.nl/ for more info

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.

Single Use Plastic Bag

Known outputs to technosphere. Products and co-products

Name	Amou	Unit	Quantity	Allocation %	Waste type	Category	Comment
Single use plastic bags to landfill	1	p	Amount	100 %	not defined	_Bag example	
(Insert line here)							

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)							

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	D	S	M	M	Comment
Polyethylene, HDPE, granulate, at plant/RER U	3640	g	L				
Stretch blow moulding/RER U	3640	g	L				
Transport, lorry 3.5-7.5t, EURO4/RER U	(3640/1000000)*100 = 0.364	tkm					100km from manufacturing to customer
Transport, municipal waste collection, lorry 21t/CH U	(3640/1000000)*10 = 0.0364	tkm					10km from home to landfill
(Insert line here)							

Input materials & resources to make 520 bags Populated by the user

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	M	Comment
(Insert line here)							

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribu
(Insert line here)				

Emissions to soil

Name	Sub-compartment	Amount	Unit	Distribu
(Insert line here)				

Known emissions & outputs from production of 520 bags Populated by the user

Final waste flows

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Non material emissions

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Social issues

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
(Insert line here)								

Economic issues

Name	Sub-compartment	Amount	Unit	Distribution
(Insert line here)				

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	S	M	M
Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	3640	g	Undefined			

What happens at the end of life? You decide and input where the product goes

HDPE

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Oil, crude, in ground	in ground	0.90726	kg	Undefined				Uncertainty for LCI results cannot be determined
Gas, natural, in ground	in ground	0.73058	m3					
Coal, hard, unspecified, in ground	in ground	0.10201	kg					
Coal, brown, in ground	in ground	2.8419E-6	kg					
Peat, in ground	biotic	0.0019149	kg					
Wood, unspecified, standing/m3	biotic	3.341E-9	m3					
Energy, potential (in hydropower reservoir), converted	in water	0.58321	MJ					
Uranium, in ground	in ground	8.5985E-6	kg					
Energy, gross calorific value, in biomass	biotic	0.31274	MJ					
Barite, 15% in crude ore, in ground	in ground	5.407E-8	kg					
Aluminium, 24% in bauxite, 11% in crude ore, in ground	in ground	1.2088E-6	kg					
Clay, bentonite, in ground	in ground	3.3058E-5	kg					
Anhydrite, in ground	in ground	3.3018E-6	kg					

Peer reviewed datasets imbedded in software
Data has been collected by others and represents actual operations

Include:
- **Known inputs**
- **Emissions to air**
- **Emissions to water**
- **Emissions to soil**
- **Wastes and emissions sent to treatment**

Ability to modify datasets based on your own data

Emissions to air

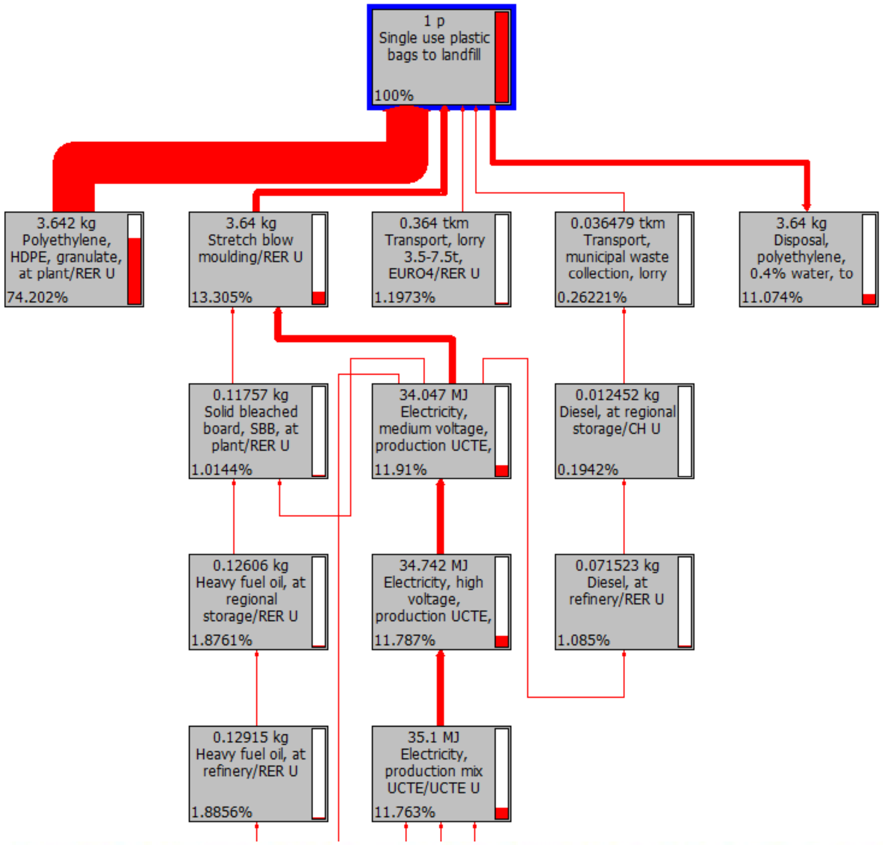
Name	Sub-compartment	Amount	Unit					
Heat, waste	high. pop.	22.394	MJ					
Particulates, > 10 um	high. pop.	0.00020576	kg					
Particulates, > 2.5 um, and < 10um	high. pop.	0.00027649	kg					
Particulates, < 2.5 um	high. pop.	0.00016075	kg					
Carbon monoxide, fossil	high. pop.	0.012277	kg					
Carbon monoxide, biogenic	high. pop.	8.5494E-5	kg					
Carbon dioxide, fossil	high. pop.	1.556	kg					
Carbon dioxide, biogenic	high. pop.	0.010835	kg					
Sulfur dioxide	high. pop.	0.0040765	kg					
Hydrogen sulfide	high. pop.	5.8431E-9	kg					
Nitrogen oxides	high. pop.	0.00323	kg					
Ammonia	high. pop.	2.1658E-10	kg	Undefined				Uncertainty for LCI results cannot be determined

Known outputs to technosphere. Waste and emissions to treatment

Name	Amount	Unit	Distribution	S	Max	Comment
Disposal, facilities, chemical production/RER U	6.3247E-10	kg	Undefined			Uncertainty for LCI results cannot be determined
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH U	0.0027192	kg	Undefined			Uncertainty for LCI results cannot be determined
Disposal, average incineration residue, 0% water, to residual material landfill/CH U	0.010073	kg	Undefined			Uncertainty for LCI results cannot be determined
Disposal, wood untreated, 20% water, to municipal incineration/CH U	4.4075E-8	kg	Undefined			Uncertainty for LCI results cannot be determined
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	0.00063407	kg	Undefined			Uncertainty for LCI results cannot be determined
Disposal, hazardous waste, 0% water, to underground deposit/DE U	0.0049779	kg	Undefined			Uncertainty for LCI results cannot be determined
Disposal, hard coal mining waste tailings, in surface backfill/kg/GLO U	0.020052	kg	Undefined			Uncertainty for LCI results cannot be determined

LCA Results - Improvement Opportunities

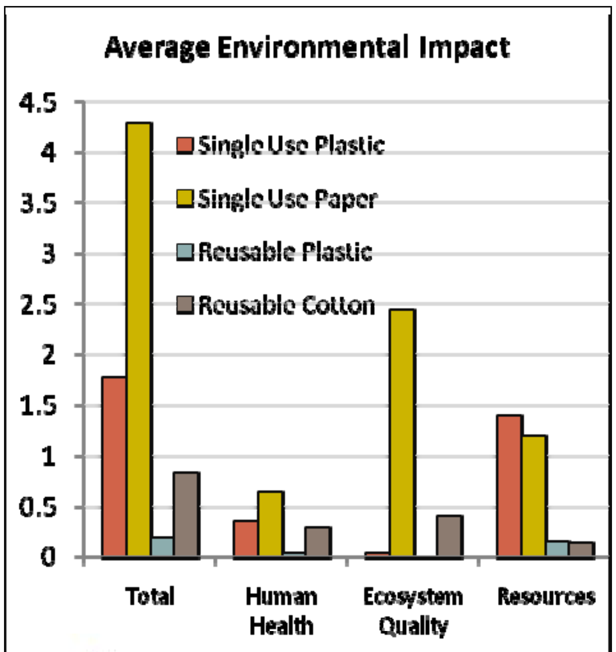
- Quantify contribution of individual materials and processes to the life cycle impact
- Understand relative contribution of processes and products

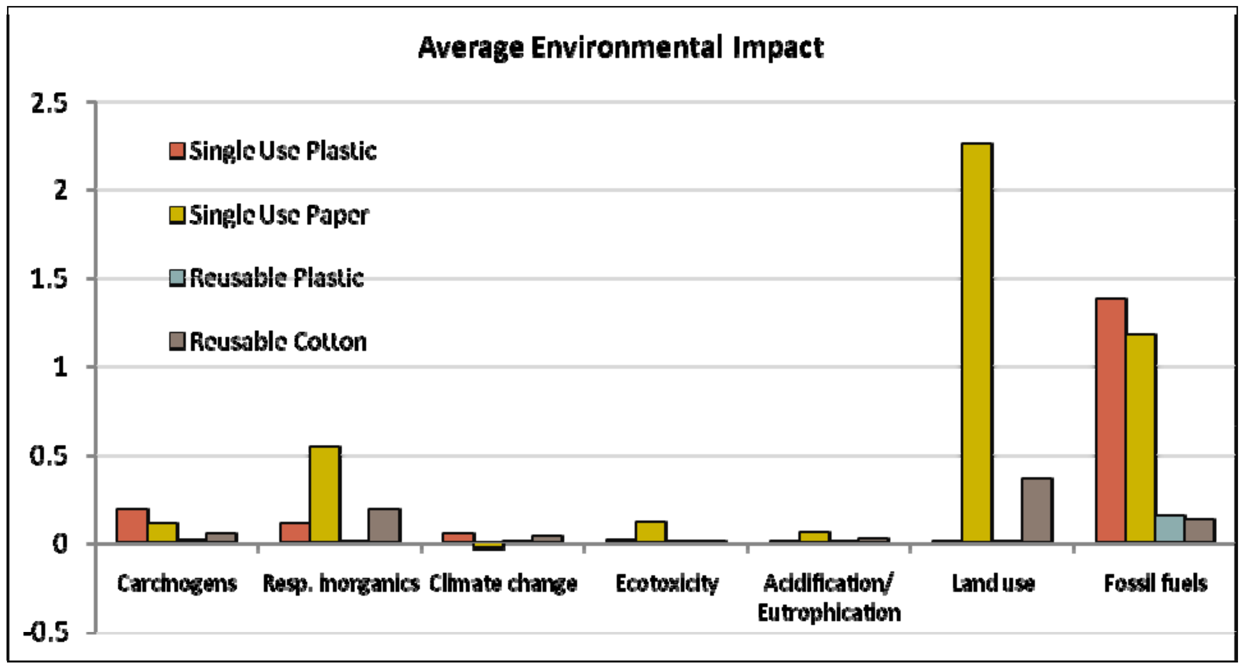


LCA Results - Product Comparisons

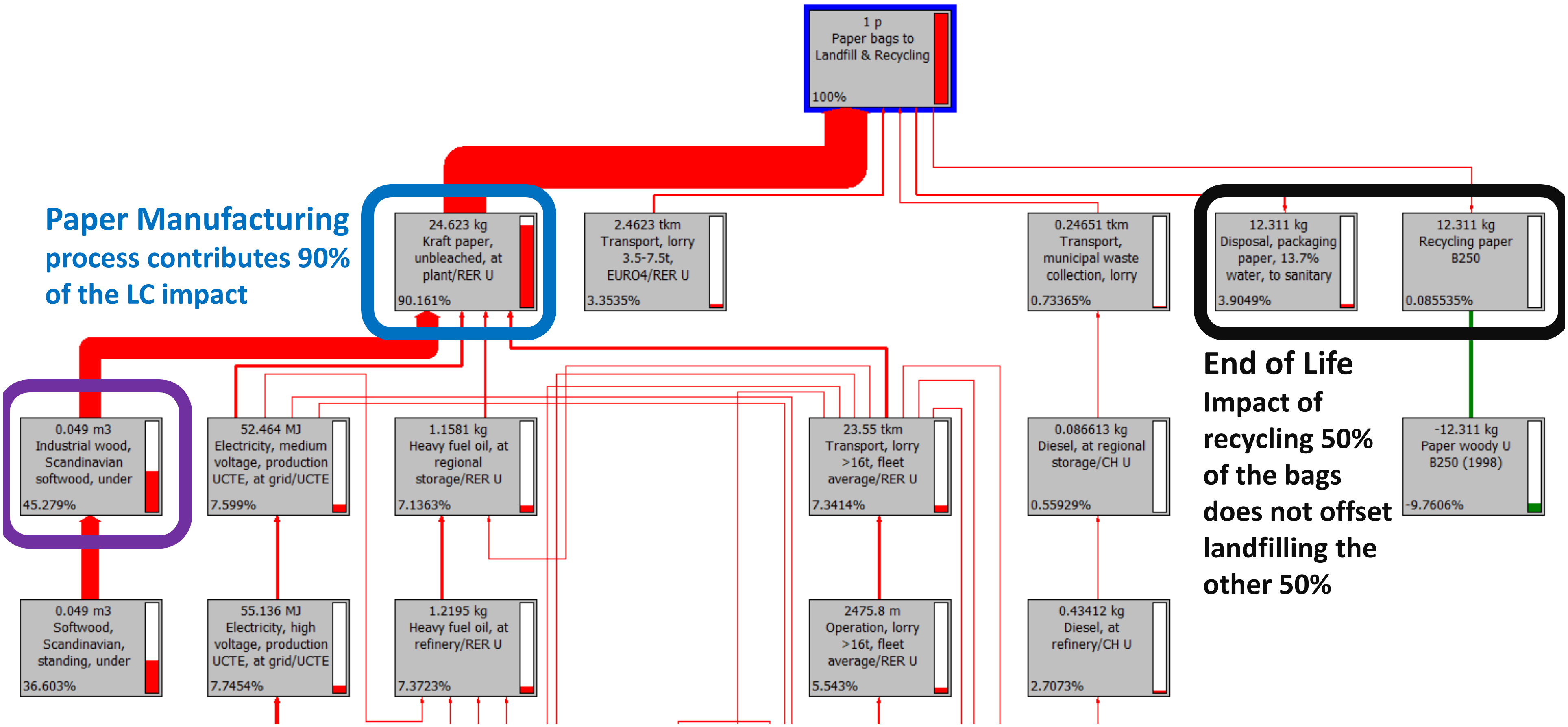
Results comparing environmental impacts of multiple products

- Used to support marketing claims
- Identify impact categories which products differ

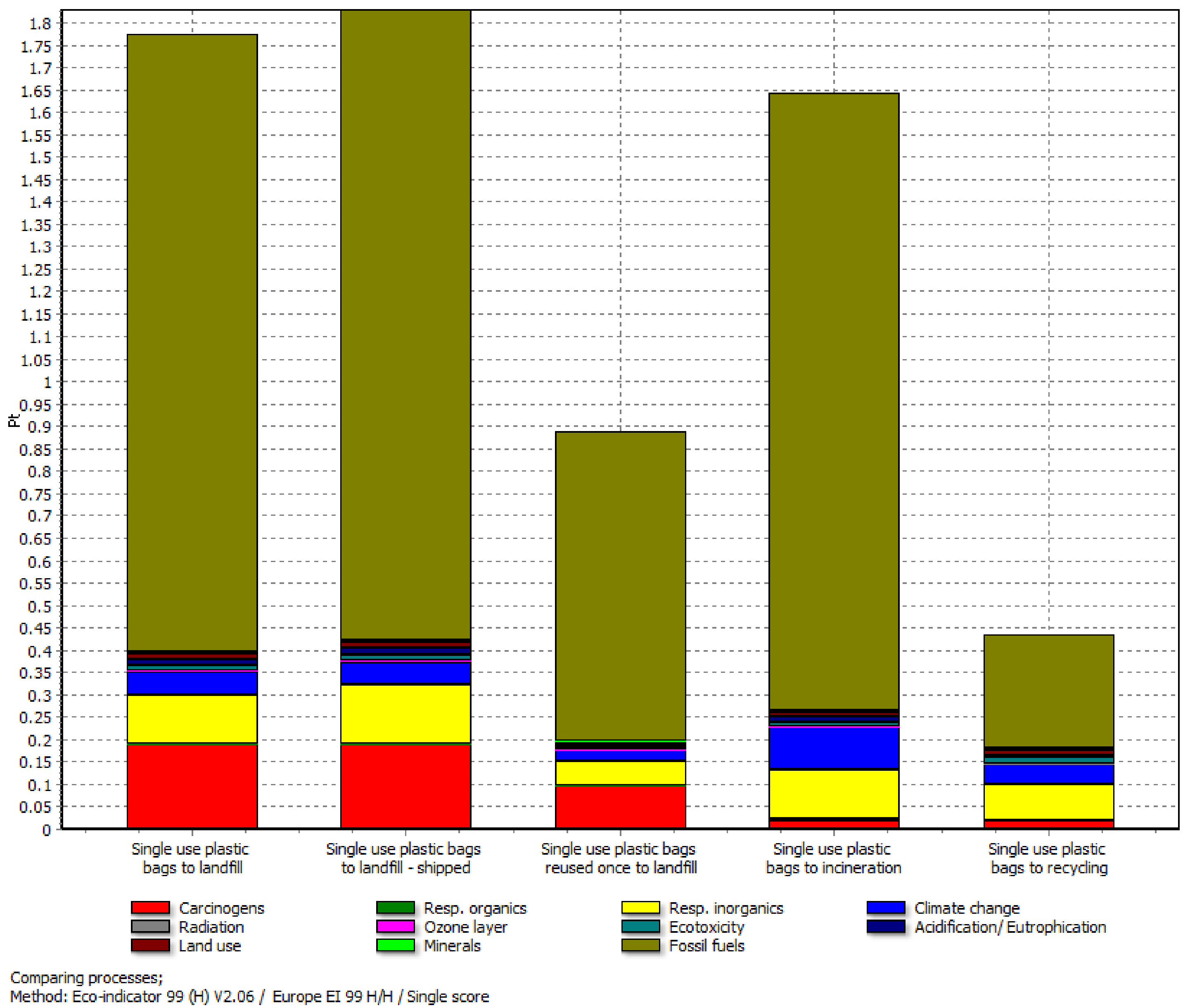




LCA Results – Paper Bags



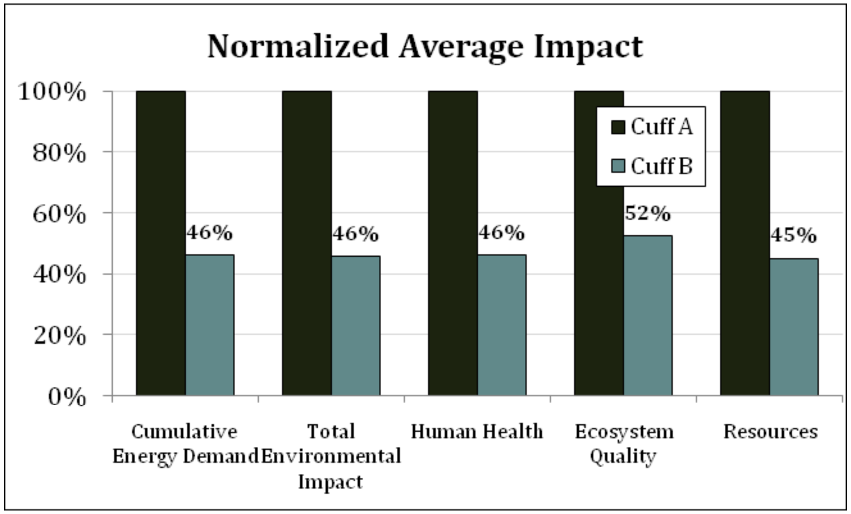
Compare Multiple Scenarios

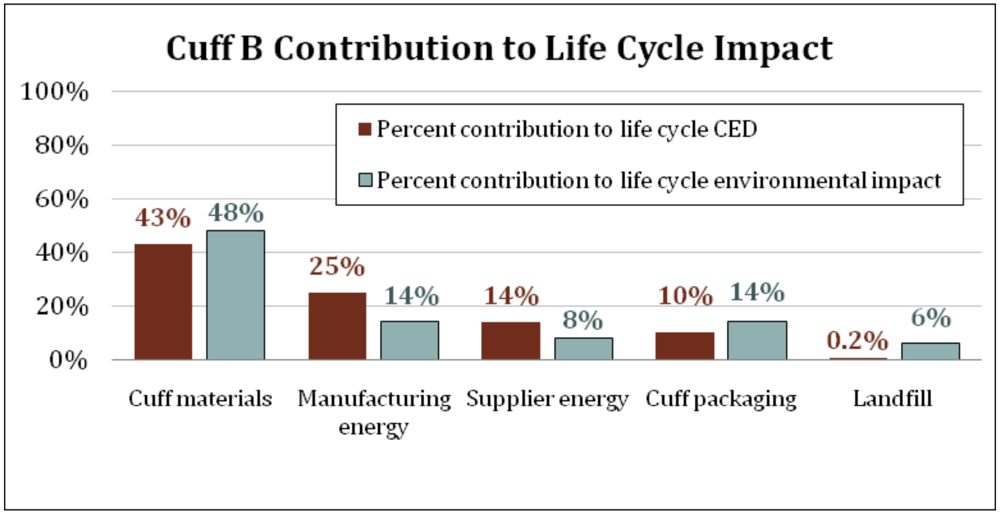


Company Examples

Comparing Multiple Blood Pressure Cuff Designs using LCA

- Objective was to compare three designs and explore multiple end of life scenarios to determine which is ideal for each cuff
- Results were used to
  - Validate the dematerialization and material choices that were made by the product designers
  - Identify operations throughout the life cycle which contribute significant environmental impact which allowed the design team to focus on those processes to further reduce the environmental impact of future designs
  - Validate environmental claims made by the manufacturer
  - Assist customers in making more informed purchasing and end of life management decisions





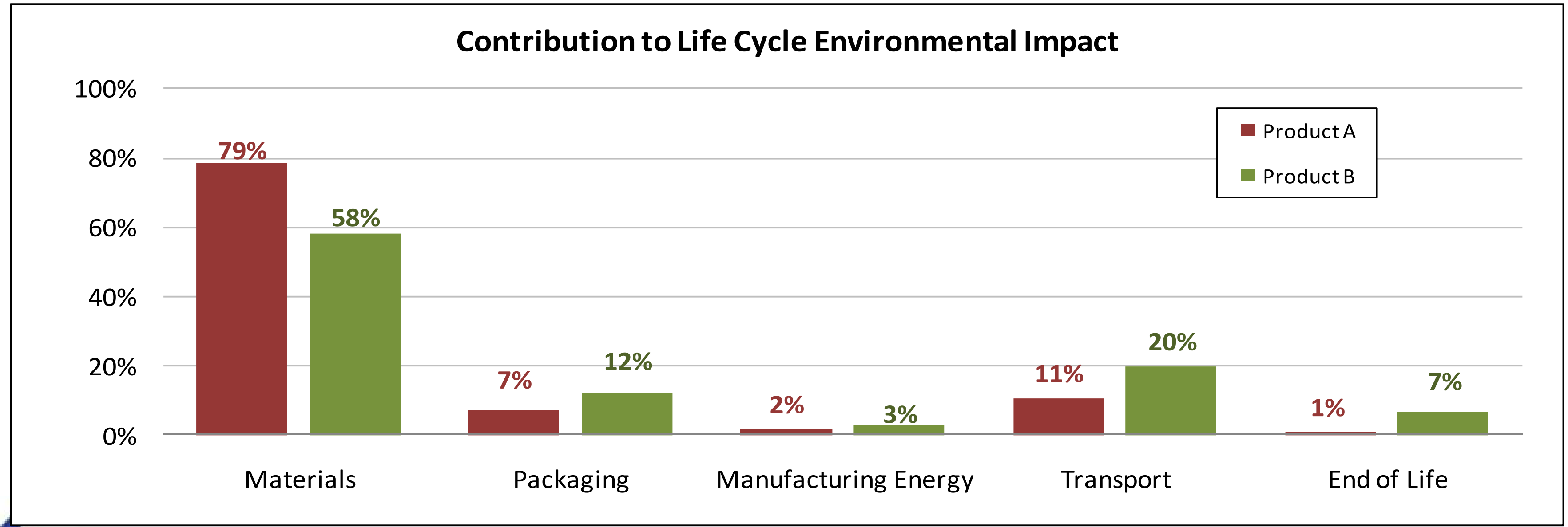
Comparing Remanufacturing & Recycling Toner Cartridges using LCA

- Objective was to determine the optimal end of life scenario (recycling or remanufacturing) and pinpoint opportunities to further improve the environmental footprint of the cartridges
- Results highlight processes that contribute significantly to energy and environmental impact which the company was unaware
  - Present a design roadmap for product designers and supply chain managers which pinpoint those processes which contribute significantly to the total environmental impact to further advance environmental performance
  - The company has used the results to communicate the environmental footprint of their products to customers, in order for customers to make more informed purchasing decisions.

LCA Results - Product Comparisons

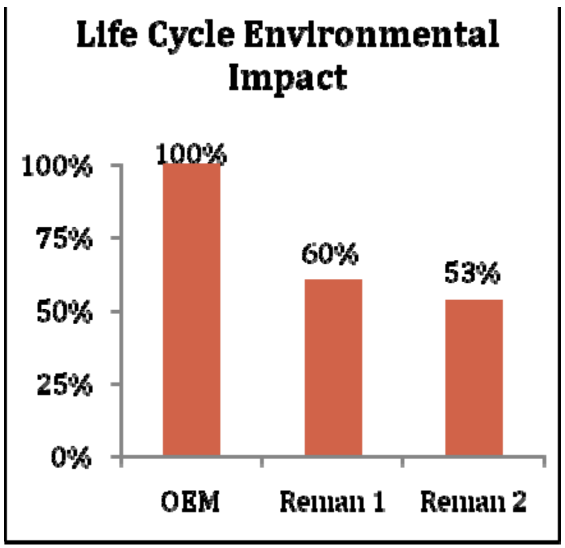
Results comparing life cycle stages impact of multiple products

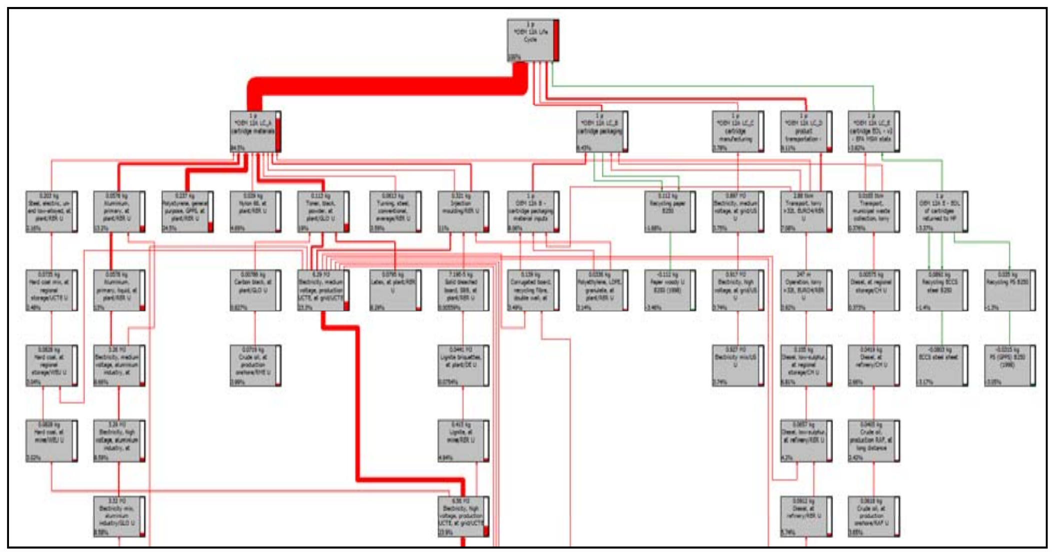
- Pinpoint contribution of stages to the life cycle impact
- Visualize differences between products



LCA & Material Reuse

- Quantify the environmental benefits of
  - Recycling materials at the end of life
  - Reusing or using recycled content materials
  - Multiple remanufacturing cycles
- Identify improvement opportunities to further reduce the environmental impact





LCA Challenges

- **Data collection**
  - Complex supply chains
  - How far back in the life cycle is data collected?
  - Analysis can be time consuming, if data not readily available
  - Engaging suppliers & end-of-use processors in data analysis
  - Is data representative of the time? Geography? Production processes?
- Accuracy of results dependent on **quality of inventory data**
- **Communicating** results can be tricky
- **Comparative LCA results** are representative of one specific case and do not represent population of a product

LCA Recommendations

- **Educate and rally** team to understand LCA as a tool and reasons for its use
- Clearly **define the goal & scope** of the LCA
- Ensure the **functional unit** is clearly defined
- **Build the LCA model** with best data physically available
- Complete **sensitivity analysis**
- Use **experienced and trained** LCA practitioners
- Follow the **ISO 14040 process** to validate marketing claims and bring recognition to the study
- **Stay up to date on LCA** research, data sources, and modeling techniques

Benefits of LCA

- **Quantify environmental benefits** of products
- Provide **credible evidence** for marketing claims
- Identify opportunities to **improve the environmental performance** of products at various points in their life cycle
- **Inform decision-makers** in industry, government or non-governmental organizations
- Select **relevant indicators** of environmental performance, including measurement techniques
- Validate product **marketing claims**
- **Instill life cycle thinking** within businesses

Thank you

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