Life Cycle Assessment of Micro/Nano products

Nanotechnology and OSWER: New Opportunities and Challenges

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Outline

Why environmental assessments in life cycle perspective are important
LCA overview
Exemplification of environmental issues in micro and nano production
Product cases on fullerenes
Other studies
Conclusion and the way forward

Potential benefits of nano technology

Material science: strength, hardness, flexibility, heat conductivity/resistance, electrical conductivity/resistance.

Medicine and biology: nano-engineered biomolecules and structures can let medicine for the first time intervene in a sophisticated and controlled way at the cellular and molecular level. disease diagnosis or molecular imaging

Information and electronics: minimization of scale of devices, optoelectronics, chips and storage

Environment: Improve efficiency of a number of environmental applications such as enhanced and self-cleaning filtration devices for the purification of water, or remediation technologies. Nanoscale solid state sensors and biosensor for detection of pollutants

Energy: Improved efficiency of energy usage, devices for enhanced exploitation of solar energy, hydrogen storage, fuel cells or nano-fabricated catalysts

Military technology: nanocomputers and nanosensors may allow a more capable surveillance of potential aggressors. Nanotechnological enhancements could make smaller, cheaper and more precise conventional weapons. A better target discrimination could minimize unintended damages in a war scenario

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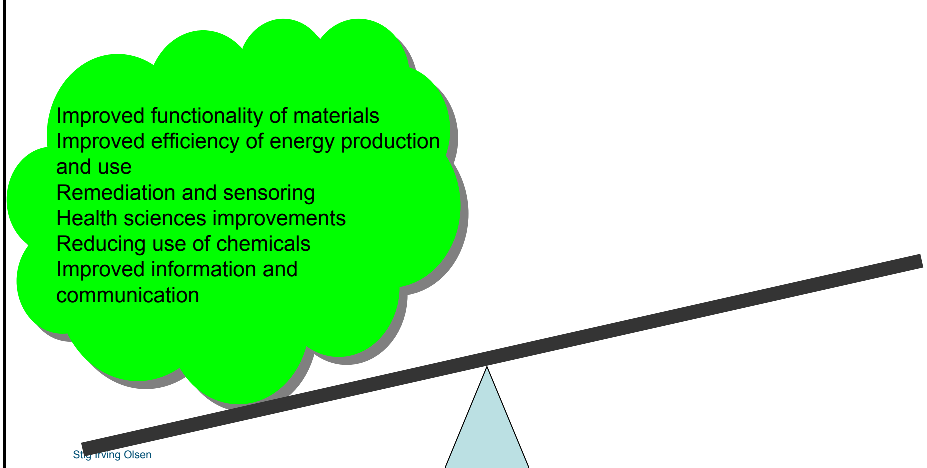

Potential environmental impacts

Toxicological risks to humans and the environment
Increased exploitation and loss of scarce resources
Higher requirement to materials and chemicals
Increased energy demand in production lines
Increased waste production in top down production
Rebound effects (horizontal technology)
Increased use of one way systems
Disassembly and recycling problems

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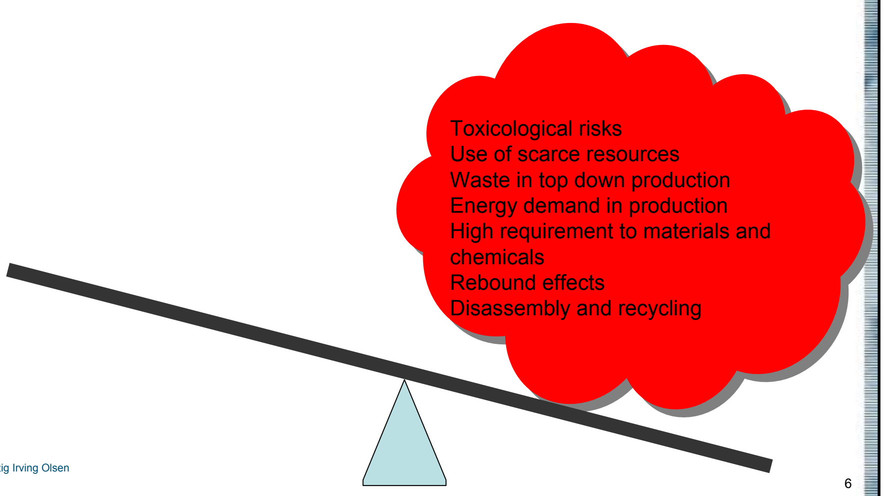

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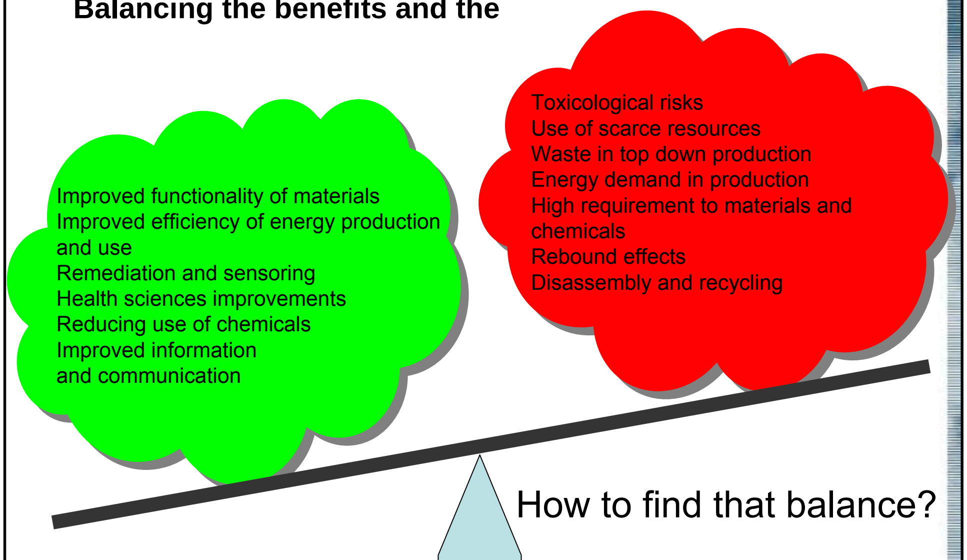
Balancing the benefits and the



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Environmental Assessment Concept – an outline

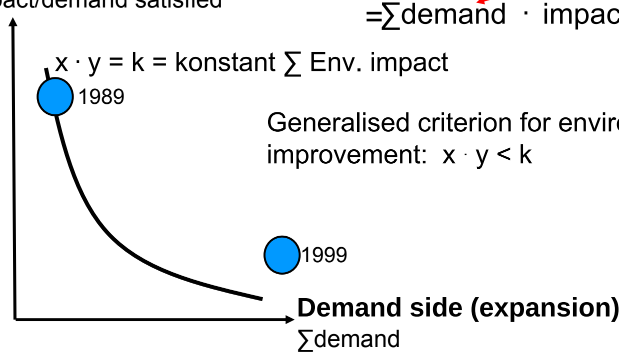
Supply side (substitution)

Eco-efficiency:
impact/demand satisfied

The Master Equation:

∑ Env. impact = P · E · T

=∑demand · impact/demand satisfied



Generalised criterion for environmental improvement: x · y < k

(After Henrik Wenzel, 2005)

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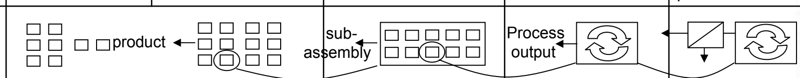
The levels of intervention for Eco-efficiency improvement in the demand-supply chain – a closer look

	Level 0	Level 1	Level 2	Level 3	Level 4
The demand & supply chain	The human need/demand ⇄	The product ⇄	The production ⇄	The process ⇄	The input/output from/to nature
The demand side	The consumer demands a product or service	The product is the demand of a chain of production facilities	The production is the demand of a series of processes/unit operations	The process demands the resulting input and output	
The supply side		The product supplies the service and satisfies the customer demand	The production facility supplies the material or sub-assembly of the product	The process/unit operation supplies the requested properties	Nature supplies the resources and receives the emissions
The system level of intervention	Not targeted by Eco-efficiency measures	The product system The product life cycle The product chain The supply chain	The company/ individual production facility in the supply chain	The individual unit operation in the production facility	The resource consumption & emission from the individual process
Pictograms of the four intervention levels	 **The product chain**		**The production facility**	**The unit operation**	**The emission**
Concepts for Eco-efficiency improvement	Life Cycle Engineering Eco-design Design for Environment		Process Integration Cleaner Production Waste Minimisation	Process Intensification Cleaner Production	Treatment

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(Reproduced from Wenzel and Alting, 2004)

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Life Cycle Thinking

•What is environmental assessment of products?

•How is the environmental impacts of a product assessed?

•Why is the environmental impacts from products interesting?

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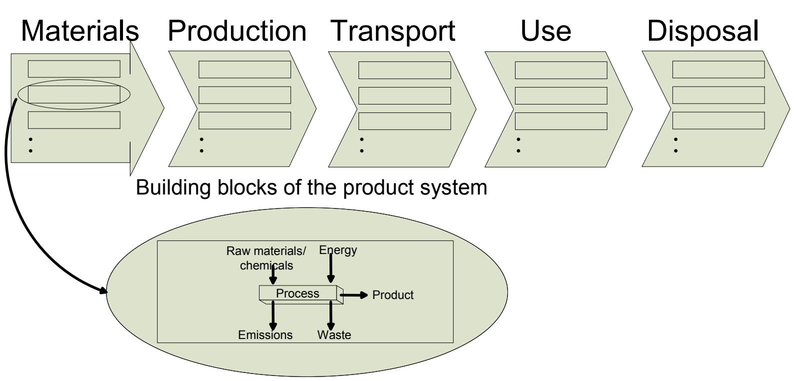
Inventory

Product system



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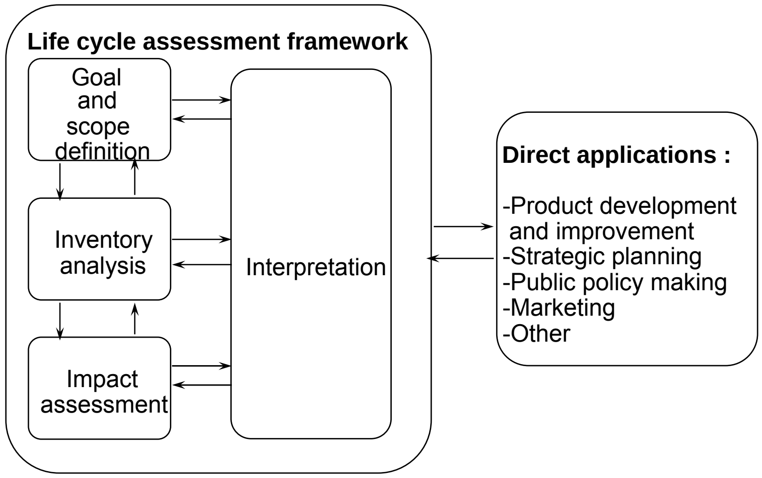
Elements of LCA



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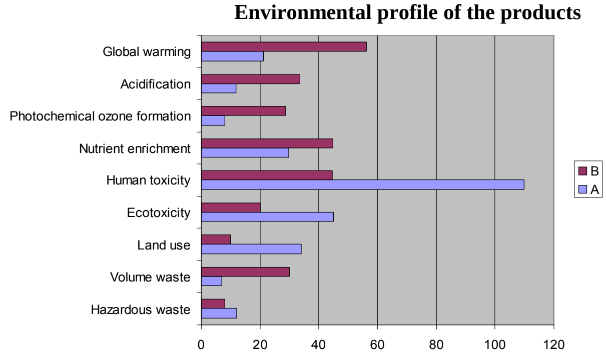
Environmental impacts

Inventory of emissions

	CAS.no.	Emission to air	Emission to water
Substance		g	g
2-hydroxy-ethanacrylate	816-61-0	0,0348	
4,4-methylenebis cyclohexylamine	1761-71-2	5,9E-02	
Ammonia	7664-81-7	3,7E-05	4,2E-05
Arsenic (As)	7440-38-2	2,0E-06	
Benzene	71-43-2 (cur	5,0E-02	
Lead (Pb)	7439-92-1	8,5E-06	
Butoxyethanol	111-76-2	6,6E-01	
Carbondioxide	124-38-9	2,6E+02	
Carbonmonoxide (CO)	630-08-0	1,9E-01	
Cadmium (Cd)	7440-46-9	2,2E-07	
Chlorine (Cl2)	7782-50-5	4,6E-04	
Chromium (Cr VI)	7440-47-3	5,3E-06	
Dicyclohexane methane	86-73-6	5,1E-02	
Nitrous oxide(N2O)	10024-97-2	1,7E-02	
2,4-Dinitrotoluene	121-14-2	9,5E-02	
HMDI	5124-30-1	7,5E-02	
Hydro carbons (electricity, stationary combustic	-	1,7E+00	
Hydrogen ions (H+)	-		1,0E-03
i-butanol	78-83-1	3,5E-02	
i-propanol	67-63-0	9,2E-01	
copper (Cu)	7740-50-8	1,8E-05	
Mercury(Hg)	7439-97-6	2,7E-06	
Methane	74-82-8	5,0E-03	
Methyl i-butyl ketone	108-10-1	5,7E-02	
Monoethyl amine	75-04-7		7,9E-06
Nickel (Ni)	7440-02-0	1,1E-05	
Nitrogen oxide (NOx)	10102-44-0	1,1E+00	
NMVOC, diesel engine (exhaust)	-	3,9E-02	
NMVOC, power plants (stationary combustion)	-	3,9E-03	
Ozone (O3)	10028-15-6	1,8E-03	
PAH	ikke specifik	2,4E-08	
Phenol	108-95-2		1,3E-05
Phosgene	75-44-5	1,4E-01	
Polyeter polyol	ikke specifik	1,6E-01	
1,2-propylenoxide	75-56-9	8,2E-02	
Nitric acid	7782-77-6 (c	8,5E-02	
Hydrochloric acid	7647-01-0 (c	1,9E-02	
Selenium (Se)	7782-49-2	2,6E-05	
Sulphur dioxide(SO2)	7446-09-5	1,3E+00	
Toluene	108-88-3	4,8E-02	
Toluene-2,4-diamine	95-80-7	7,9E-02	
Toluene diisocyanat (TDI)	26471-62-5	1,6E-01	
Total-N	-		2,6E-05
Triethylamine	121-44-8	1,6E-01	
Unspecified aldehydes	-	7,5E-04	
Uspecified organic compounds	-	1,5E-03	
Vanadium	7440-62-2	1,8E-04	
VOC, diesel engine (exhaust)	-	6,4E-05	
VOC, stationary combustion (coal fired)	-	4,0E-05	
VOC, stationary combustion (natural gas fired)	-	2,2E-03	
VOC, stationary combustion (oil fired)	-	1,4E-04	
Xylene	1330-20-7	1,4E-01	
Zinc (Zn)	7440-66-6	8,9E-05	

Global warming	174.000	kg CO_2- equ.
Ozone depletion	0	kg CFC11- equ.
Acidification	868	kg SO_2- equ.
Photochemical ozone formation	200	kg C_2H_4- equ.
Eutrophication	3.576	kg NO_3^- equ.
Toxicity to humans	$3,40 \cdot 10^{11}$	m^3 air
Ecotoxicity	$2,16 \cdot 10^{7}$	m^3 water
Land use	170	ha·yr
Bulk waste	9.450	kg
Hazardous waste	248	kg

Environmental profile of the products



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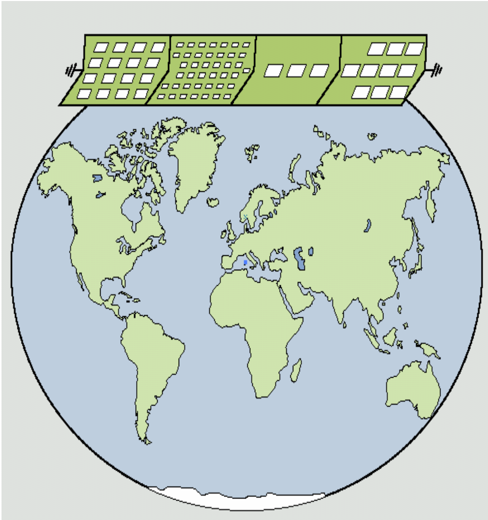
Environmental impact assessment in LCA

- The Life Cycle is *global*
- The product system extends over time
- Focus is on a single product
- The assessment predicts impacts not actual effects



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Characteristic features of LCA

Focus on services (the functional unit) ➠ products

Holistic perspective

- life cycle from cradle to grave
- all relevant environmental impacts, resource consumption (biotic and abiotic) and sometimes working environment
- Identification of problematic impacts

Comparative (relative statements)

Aggregation over time and space

- The life cycle is global
- The life cycle may last for decades or centuries

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How is an LCA performed?

Three levels with increasing extent of detail, effort of work and strenght of decision

Stops when question is answered with adequate certainty

1. Life Cycle Check
2. Life Cycle Screening
3. Detailed Life Cycle Assessment

To perform an LCA imply an iterative approach – *also within each of the three levels*

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Elements in a Life Cycle Check

- Choice of product
- Identification of the service - the functional unit
- Establishing boundaries for the product system
- Collection of data
- Preliminary environmental assessment – the MECO principle
- Interpretation

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Life Cycle Check – the preliminary environmental assessment

The MECO principle

	Life Cycle Phase			
Reasons for Environmental Impact	Extraction of raw materials	Production	Use	Disposal
Materials				
Energy				
Chemicals				
Other				

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Life Cycle Check

	ife Cycle Phase			
Reasons for Environmental Impact	Extraction of raw materials	Production	Use	Disposal
Mate ials				
Ene gy				
Chemicals				
Other				

Strenghts of the MECO analysis:

- It covers the whole Life Cycle
- All environmental impacts are included through the choices and actions that causes them
- Simpel and quick
- Sometimes provides adequate answers
- Identifies needs for more detailed analyses

It is used quantitative or qualitative

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Environmental input output analysis

- The economic input-output life cycle assessment (EIO-LCA) relates economic activity across sectors to energy requirements and environmental discharges
- input-output matrix of economic activities is used to calculate economic activity generated across all sectors by purchases in a particular sector. It also uses public datasets, such as EPA’s Toxic Release Inventory (TRI), to calculate unit environmental output per unit economic output for each sector.
- The model provides aggregate results and therefore does not distinguish between different grades or types of materials produced in the same sector.

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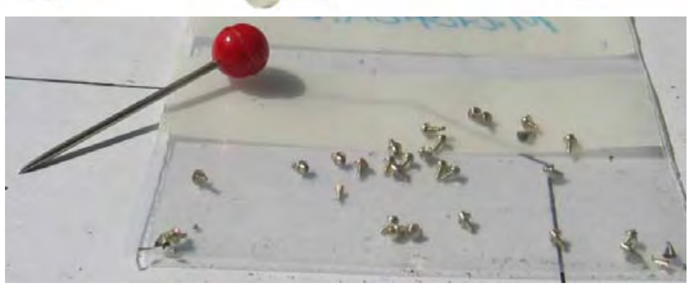
Some materials issues in micro manufacturing

Micro screw for hearing aid



Ordinary turning produces more than 50% metal waste
Cold forging puts requirements to materials

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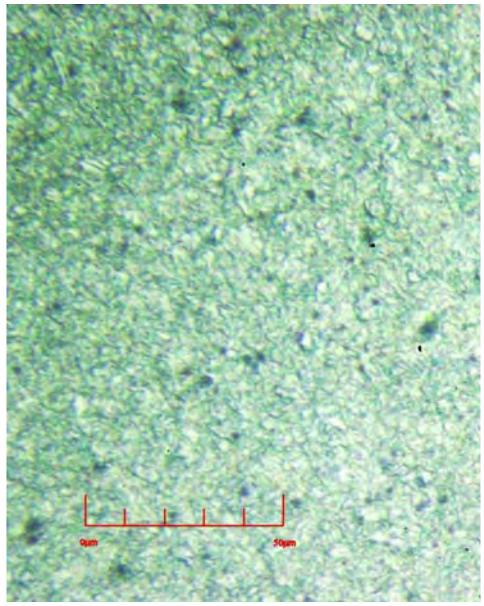
Material analysis

Micro structure

- Homogenious material
- Small grains

Better specifications must be met

Withen og Marstrand



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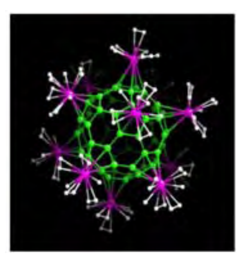
Use of scarce resources

More frequent use of rare metals due to reduced importance of price in the single product and/or specific properties
Rare metals imply higher energy use in extraction (e.g. Gold is 2000 times more energy intensive than steel)

For example the use of gallium arsenide in electronics
Or the use of other types of metals in Endo- or ectohedral fullerenes
For example Carbon trimetaspheres in which lathanide series metals incorporated inside (e.g. galolinium)



Three-dimensional Scandium (pink) C60 (green) complex with 8.7 wt.% total H2 (white) capacity and 7.0 wt% reversible hydrogen storage.
Dillon et al., 2006.
Mater. Res. Soc. Symp. Proc. Vol. 895

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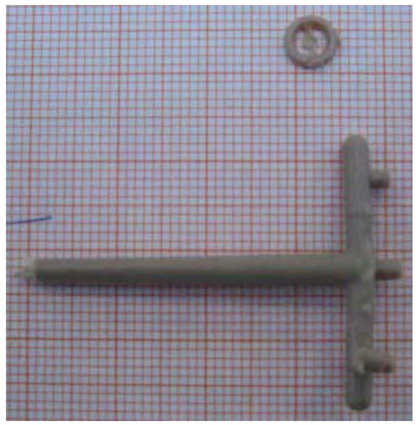
Some materials issues in Micro manufacturing

Micro injection moulding – big runners are necessary for handling and assembly – up to 99% of the total weight is waste



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Problems with recycling:

Material quality reduction

Disassembly

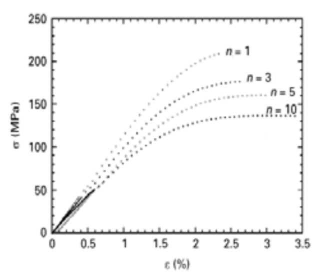

Figure 6 Stress–strain curves of recycled CPEEK30.

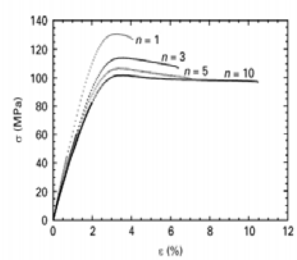

Figure 5 Stress–strain curves of recycled CPEEK10.

Sarasua & Pouyet, 1997

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Top down production

Inputs	*Outputs*
460 kWh energy	0.007 kg silicon wafer
1.7 m^3 water	1.7 m3 waste water
1.0 kg inorganic acid	3.3 kg inorganic waste/emission
2.3 kg inorganic chemical	0.7 kg organic waste/emission
5 kg nitrogen	
0.1 kg other technical gases	
0.7 kg organic chemicals	

From K. Schischke, O. Deubzer, H. Griese, I. Stobbe, 2002

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Waste management issues

Waste hierarchy
- prevention
- recycling/reuse
- Energy recovery
- disposal

How does NT fit into this?

Over the life cycle probably not prevention due to waste produced in raw materials extraction and production stages

Recycling is seen to be difficult with current technologies for small amount (problems related to e.g. disassembly) as seen for electronics today

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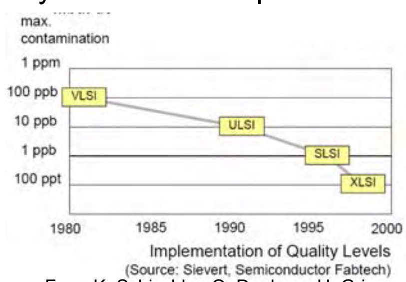
Some energy issues in Micro manufacturing

Clean room requirements increasing:
HVAC (heating, ventilation and air conditioning)

class 10,000 2280 kWh/m^2
class 100 8440 kWh/m^2

High purity of chemicals – purification energy requiring



(7% of total energy use by US chemical industry)

From K. Schischke, O. Deubzer, H. Griese, I. Stobbe, 2002

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Production of a digital telephone

Main group	Mass (g)	TPI (*1000)	GWP (g CO_2 equivalents)	ADP (g/year)	EPS (ELU)	Eco99 (millipoints)
Mechanics	941	130	9049	589	3087	623
Frequency determined components	0.5	3	25.2	0.3	1.3	1.3
Discrete semiconductors	77	21	1044	4	9	47
Electromechanics	53	19	440	55	311	46
Passives	8	33	599	4	262	26
Magnetic	14	42	403	26	142	23
Integrated circuits	6	9	1637	102	566	998

Andræ, 2002. PhD Thesis
Chalmer University of technology

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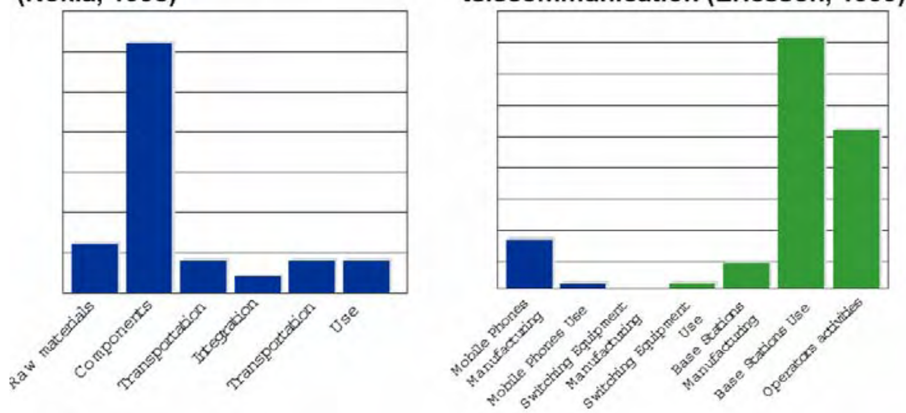
Energy burden of a mobile phone (Nokia, 1998) / Energy burden of mobile telecommunication (Ericsson, 1999)



From K. Schischke, O. Deubzer, H. Griese, I. Stobbe, 2002

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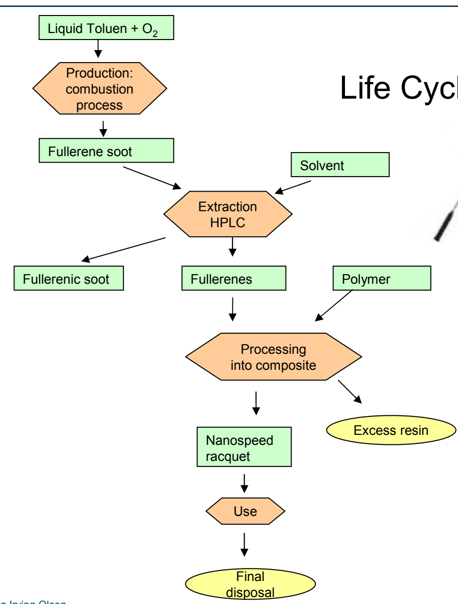
Life Cycle of a badminton racket



Producer of fullerenes
40 ton in 2003
300 ton in 2007

Processes evolve:
95% purity is anticipated

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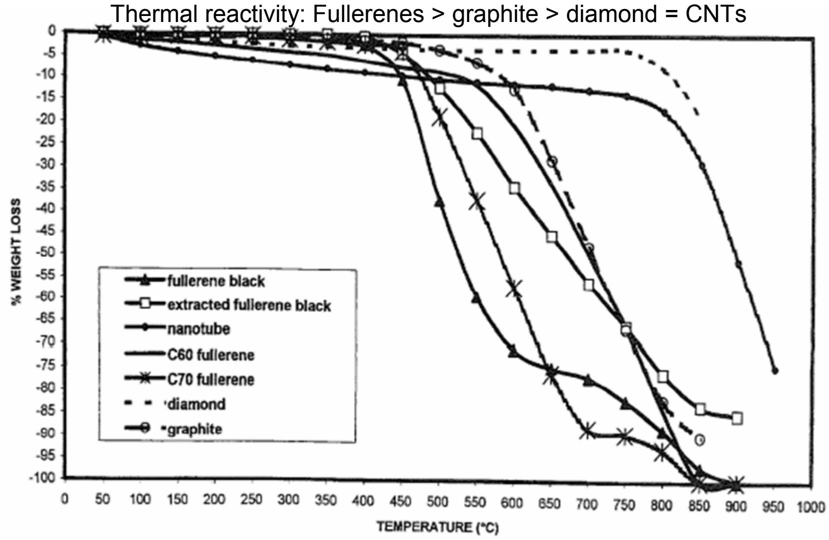
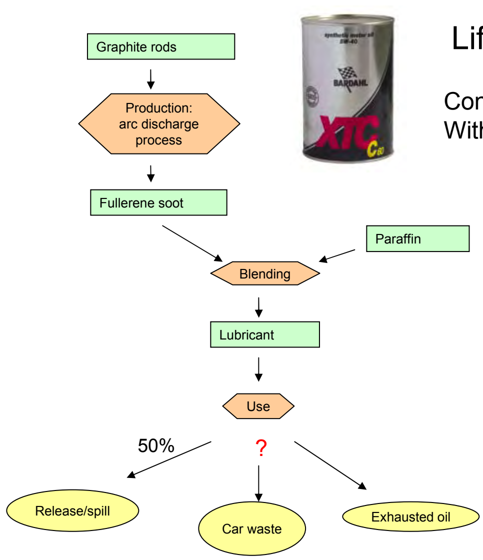
Thermal reactivity: Fullerenes > graphite > diamond = CNTs

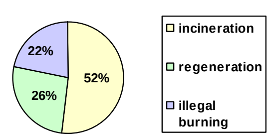


Cataldo, F, 2002. Fullerenes, 20(4), p.293-311

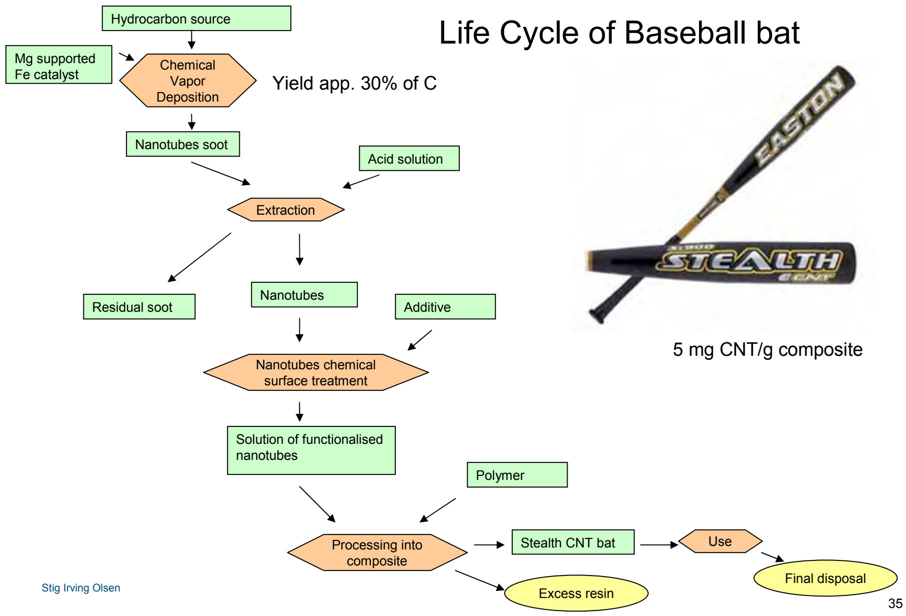
Life Cycle of a motor oil

Content 9% fullerenic soot
With a content of 7% fullerenes





Life Cycle of Baseball bat



From Haum et al, 2004 IÖW

Table 3: Overview production processes of nanotechnology

Nanotechnology based products	Nanostructure	Manufacturing process	potential hazards	industrial sector
Application Area: New Surface Functionalities and Finishing				
tribological layers: e.g. superhard surfaces	ultrathin layers; nano-crystallites; nano-particles in an amorphous matrix	vapour phase deposition, PECVD	PVD/CVD production process: risk of disposal of nano-particles is small (process is running in a vacuum environment) use stage: low scale disposal of nano-particles possible	engineering, automotive
thermal and chemical protection layers	ultrathin layers; organic-inorganic hybrid-polymers; nanocomposites	vapour phase deposition; sol-gel		aerospace, automotive, ICT, food
self-cleaning and antibacterial surfaces	ultrathin (polymer) layers, nano-crystallites in an amourphous matrix	vapour phase deposition, sol-gel, soft lithography		textile, ICT, food, building, medicine...
scratch resistant and anti-adhesive surfaces	ultrathin layers; organic-inorganic hybrid-polymers	sol-gel; SAM	use stage: low scale disposal of nano-particles possible	building, automotive, textile, consumer goods
products with "nanoparticle effects" : e.g. colour effects in lacquers	nano-particles, ultrathin layers	flame assisted deposition, flame hydrolysis, sol-gel	production: deposition possible; use stage: low scale disposal possible	building, automotive, consumer goods, textile
Application Area: Catalysis, Chemistry, Advanced Materials				
catalysts	nanoporous oxides, polymers or zeolithes; ultrathin layers	precipitation, sol-gel, SAM, molecular imprinting	not known	chemistry, automotive, environmental, biotech
sieves and filtration	sintered nano-particles, nanoporous polymers	self assembly, colloid chemistry		chemistry, environmental
Application Area: Energy Conversion and Utilisation				
fuel cells	ceramics from sintered nano-particles	div.	not known	energy, automotive
super-capacitors	nanotubes, nanoporous carbon aerogels	div.	nanotubes possibly toxic when inhaled	energy
superconductors	ultrathin layers	e.g. vapour phase deposition	production: risk of disposal is small	energy, medicine
Application Area: Construction				
nanoscale additives: e.g. carbon black in car tires	nanocrystals and -particles	flame assisted deposition, flame spray pyrolysis	production process: disposal of nano-particles possible, danger of inhaling for workers; use stage: low scale disposal of nano-particles possible	building, automotive
nanoparticle-reinforced products: e.g. temperature resistant components	(amorphous) nano-particles	flame assisted deposition, flame hydrolysis		automotive, ICT, consumer goods, medicine, aerospace
Application Area: Information Processing and Transmission				
nanoelectronic components	ultrathin lateral nanostructured semiconductor	PVD, CVD, lithography	PVD/CVD production process: risk of disposal of nano-particles is small	ICT
Displays	utrathin layers	PVD, spin-coating		ICT, automotive
Application Area: Nanosensors and Nanoactuators				
sensors: e.g. GMR-sensors	metallic ultrathin layers; ultrafine tips	CVD/PVD/MBE; etching, SAM	PVD/CVD production process: risk of disposal of nano-particles is small	automotive, engineering, ICT, analytics
probes e.g. for scanning tunneling microscope	utrathin layers, ultrafine tips and molecules	PVD, etching, SAM		analytics
Application Area: Life Sciences				
active agent carrier: e.g. drug carriers	organic molecules, nanoporous oxides	self assembly, anodic treatment	flame hydrolysis production process: disposal of nano-particles possible; use stage: particles might be absorbed dermally; very small TiO_2-particles possibly toxic	Pharma, medicine
Cosmetics: e.g. pigments	utrathin layers from nano-particles, (amorphous) nano-particles	wet-chemical separation; colloid chemistry		cosmetics
sunscreen	nanocrystalline titanium dioxide (TiO_2)	flame hydrolysis		cosmetics

Source: IOW

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LCA of Nano technologies

Mentioned specifically as a research area in official reports

Only few studies has as yet been identified:

Carnegie-Mellon University
Two studies: Nanocomposite automotive body parts
Automotive catalysts

IÖW (Institute for ecological economy research)
Ecological efficiency of nanovarnish
Process innovation with styrene synthesis
Nano-innovation within the display sector
Nano-applications within the lights sector

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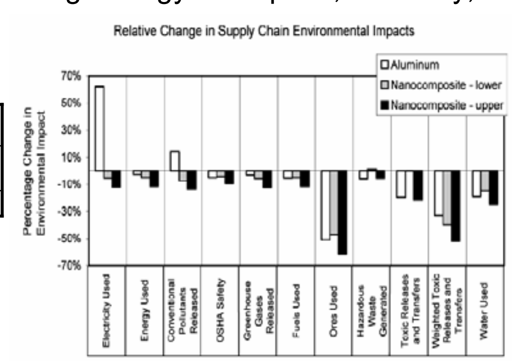
Carnegie Mellon studies (1)

Combination of process based and EIO LCA
-Steel→ nanocomposite or aluminum – weight reduction
-Design requirements e.g. energy absorption, durability, costs etc.

	Mass reduction	CO_2 - savings
Nanocomposite	38-67%	4.6 – 8.5%
Aluminum	50%	5.5%



(Lloyd and Lave, 2003)

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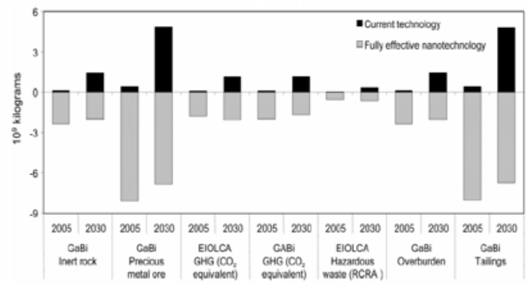
Carnegie Mellon studies (2)

Reduction of PGM (platinum group metals) in automotive catalysts

-Using Nanotechnology a 95% reduction is feasible by controlling shape, size and location of PGM particles



(Lloyd et al., 2005)

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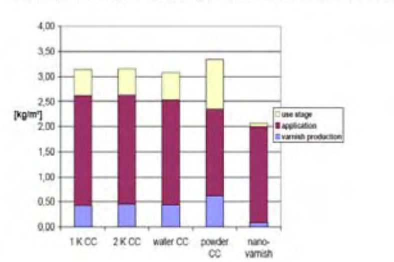
Studies from IÖW (1) *(Steinfeldt et al., 2004)*

Nano varnish

Graph 3: Global warming potential (kg-CO_2 equivalents/m² coated aluminium-car surface)



Styrene synthesis: Nanostructured catalytic converters

50% energy reduction

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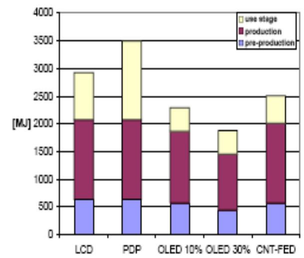
Studies from IÖW (2) *(Steinfeldt et al., 2004)*

Displays (many assumptions due to immature technology)
Reduction of energy use in LC of 20% feasible



Nanotechnology in lights sector:
White LEDs compared to traditional tungstenlamp and fluorescent lamps. LEDs more efficient than tungsten lamps but still significantly less so than fluorescent lamps.

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Environmental Assessment Concept

Foresight concept	Life Cycle Assessment concept	Scope of assessment
1. order assessment	Induced → Nanotechnologies → Application	Substitution - supply side only
2. order assessment	Avoided → Alternative technology → Application	Compare **eco-efficiency**: impact/satisfied demand
3. order assessment	Rebound effects - technology induced changes of the demand side	Expansion - demand side also Include impacts of changes in demand

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Challenges for future work

Nanotechnology is an enabling technology and probably introduces radically new technologies of production and functionalities of products

Implementation of techniques for technology forecasting in environmental assessment – scenarios, roadmapping, others?

Prospective LCAs

- Data for marginal technologies
- Inventory data for nanotechnologies

Making environmental concern inherent to nano research

Interpreting risks during the life cycle

Overall policy recommendations for research

Visions for the anticipated use => shaping the attention and priorities for environmental concern

Environmental screening of research proposals

Environmental concerns as part of research: Internal/external competence. Independence. Dialogue