Indicators for resources and resource-efficiency: a Danish perspective

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Abstract: The specific material flows and use of energy and land, which cause severe environmental and health problems in Denmark, are delimited by a risk assessment. Resource-efficiency is defined in terms of material flows and is estimated to be 0.07 without unused flows and 0.04 with unused flows for Denmark, 1990. It is shown that the path to both a global sustainable environment and welfare goes through increasing resource-efficiency, increasing lifetime of products, detoxification, dematerialisation of welfare and increasing quality and quantity of ecosystems.

An indicator system for Denmark consisting of a pyramid structured by formal indicators is proposed. At the top of the indicator pyramid are indicators for aggregated material and energy flows, almost unaffected nature and the flows of dangerous substances. The formal indicators represent flows of resources and emissions, resources and emissions related to ecological space, economic turnover and number of inhabitants as well as resource efficiency, lifetime of materials and material welfare.

Keywords: indicators; material flows; resources; resource-efficiency; sustainable development; environment; ecological space; emissions.

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1 Introduction

Resources are indispensable for economic activity and the wealth of humanity. To achieve sustainable development resources must be consumed thoughtfully to ensure to what degree and in which way they end up as waste and emissions. In relation to the environment and health the objective of this study is to investigate how to create indicators for:

- the consumption of resources
- resource-efficiency

As a result of a growing world-population, increasing material consumption in the rich countries, and the wish of poorer countries to increase their wealth, the withdrawal of resources and the resulting damage to the environment are increasing. Furthermore the fight for control of resources has historically resulted in international conflicts and wars.

Weizsäcker [1] tried to calculate the ecological space per EU inhabitant assuming the existing global resources to be evenly globally distributed and Hueting [2] investigated how much the level of production has to be reduced so as not to exceed the carrying capacity of nature. Bringezu [3] showed that the ecological rucksack for resource exploitation is increasing along with improvements in mining technology, which makes exploiting of low quality ores possible.

Spangenberg *et al*. [4] determined two types of driving forces leading to environmental problems:

– the specific chemical characteristics of substances in small quantities
– the quantitative effect of large amounts (material flows, energy flows and use of land)

At the input side of the German economy they identified 20,000 entry points and 200 substances. At the output side they estimated 2 million exit points and about 1.5 million substances. They also suggested a method for categorising land use according to the degree to which the land is dominated by humans. Land uses are divided into four categories: nature, extensive and ecological agriculture, intensive agriculture and city areas.

The DPSIR-model was evaluated by Eurostat [5] EEA and OECD to be the most appropriate model for structuring environmental information. Eurostat selected ten policy areas for which pressure indicators were developed among which were climate change, biodiversity, ozone layer depletion, exhausting of resources, dispersion of toxic substances, water pollution and water resources. Berkhout [6] focused on aggregated material flows and indicators. Eurostat [7] also did a methodological guide for economy-wide material flow accounts (MFA) and derived indicators defining aggregated flows at the input side (DMI, TMI and TMR), the output side (DPO, TDO, TMO), addition to stock (NAS) and material consumption (DMC, TMC).

Physical input-output tables (PIOTs) for the economy have been compiled for the Netherlands (1990), Denmark (1990) and Germany (1995) and can be combined with MFA [6]. Jensen compiled PIOTs for Denmark, 1990 [8] combined PIOTs with energy accounts and accounts for air emissions in NAMEA, 1990–92, 2000 [9], and did DMI and TMR indicators for Denmark (1981, 1990, 1997) for total flows and flows disaggregated into lines of business [10].

The UN Commission for Sustainable Development (CSD) [11] worked out a set of indicators, showing the road to sustainable development, and showing if we are moving in the right direction. OECD [12] developed a key set and a broader core set of indicators for sustainable development. The indicators were organised according to environmental problems such as climate change, air pollution, biodiversity, and waste and water resources.

The EU-Commission [13] worked out a strategy for sustainable development containing social, economic and environmental progress. By the criteria of severity, time, irreversibility and European and international dimensions the Commission selected the following six priorities:

1 public health

2 climate change and clean energy

3 management of resources

4 poverty and social expulsion

5 ageing and demographic features

6 mobility, land-use and territorial development.

The European Thematic Centre of Waste and Material Flows (ETC/WMF) [14] is developing a set of key indicators, which can be used by EEA for reporting on progress among the European countries on waste prevention, waste handling and material flows. The Danish Government [15] has proposed a set of superior and transverse key indicators as well as specific indicators for economic sectors. The indicators will monitor the progress and results according to the Danish National Strategy for Sustainable Development.

2 Resources

The material elements of the earth are almost constant. The earth can be divided into the outer spheres – atmosphere, biosphere, hydrosphere, and lithosphere – and the core. The biosphere, atmosphere, hydrosphere and lithosphere are very thin outer layers of the globe, whereas the core is more than 99.9% of the earth volume and mass. Thus the goal of sustainable development is to keep the outer thin layers of the earth in a good and healthy condition taking care of the organic life in these thin layers.

More than 90% of the atmosphere, hydrosphere and biosphere consists of the four elements H, O, N and C. Elements with a higher atomic mass than Fe are rare on the earth, since these elements have their origin from super nova explosions and neutron stars, whereas elements lighter than Fe (and Fe) are created by normal stars like the sun.

Thus the metals Na, Mg, Al, Si, K, Ca and Fe are very common on earth, whereas metals like Cu, Zn, Ag, Cd, Hg and Pb are rare. During evolution, organic life has been used to the common metals, whereas the more rare metals can be toxic to organic life, especially in their ionic forms.

The non-metallic elements N, P, S and Cl are very common on earth, whereas As, Se, Br and I are rare. The non-ionic form of the halogens – F, Cl, Br and I – have high oxidation potentials and are very reactive to organics. Most of their organic compounds are toxic to life.

Minerals are the building blocks of the outer earth crust. The outer earth crust varies from approximate 70 km at high mountains to 6–8 km under the oceans due to the thesis of isostasia. Since the area of earth is 5.1×10^8 km^2 and assuming a mean thickness of 20 km, the volume of the earth crust is approximately 10^{10} km^3.The layers of the earth crust from the bottom are: basaltic, granite and sediments. Under the oceans the layer of granite is missing, since the granite is created through the folding of the ocean bottoms into mountains.

Minerals are geologically often divided into granite and ores and subdivided according to their chemical and structural composition: elements, sulphides, halogen compounds, oxygen compounds, carbonates, sulphates, silicates and organic minerals. For resource purposes minerals are often divided into metallic minerals and non-metallic minerals, due to their refining, use and economic value. Thus clay is listed as a non-metallic mineral although clay minerals contain aluminium and silicium and often other metals too, since clay has a capacity for ionexchange.

It is important to measure resources because of:

- value: economic, ethical, health, needs, educational etc.
- scarcity: regeneration of renewable resources, discovery of new resources
- control: conflicts, distribution of resources and resource use
- devastation: fragmentation, pollution, protection, sensitivity
- environmental and health implications during production and consumption

Scarcity occurs when demand exceeds supply. Humans strive to control resources, and scarcity results in price increases and sometimes in conflicts and wars.

From the perspective of the environment and health it is important to measure resources because of their value for the environment and health, and because resources end up as waste and emissions after use. From a pure viewpoint of measurement it is easier to measure resources than emissions, because the number of resources and entry points are relatively small, whilst the number of exit points, products and substances in emissions are huge as shown by Spangenberg [4]. The stock of resources in nature and society, as well as the flow of resources from nature to society, is important. To achieve sustainable development the stocks of resources have to be maintained. The flow of resources has to follow the law of mass conservation as well as the two laws of thermodynamics on energy conservation and entropy. The law of entropy tells us that the flows of masses and energy in a closed space only will pass from low entropy to high entropy.

It is proposed that resources are listed and categorised according to the UN SEEA-system (2001) [16]. The SEEA-system contains the following main categories:

EA.1: *Natural Resources*: mineral and energy resources, soil resources, water resources and biological resources

EA.2: *Land and surface water*: city, agricultural, waterbodies, other

EA.3. *Ecosystems:* terrestrial, aquatic

EA 4: *Intangible*: mineral exploration, licences and concessions, permits, environmental assets

Resources, which are interesting in a Danish perspective, can be listed and categorised according to the UN SEEA-system modified into which part of nature they originate from (Table 1 and Table 2):

Table 1 EA1: Extraction of natural resources used in Denmark (tons/year)

Part of nature	*Resources*	
Lithosphere	Fossil fuels	Coal, oil and gas
	Metallic minerals	Heavy metals
		Light metals
	Non-metallic minerals	Stone, sand, gravel, clay phosphate, potash, calcium
Biosphere	Timber	Hard timber, soft timber
	Crops and plants	Yielding repeat
		Yielding one-time harvest
	Animal resources	For slaughter
		For breeding
Hydrosphere	Aquatic biological resources	Fish, shellfish
Atmosphere		Nitrogen, oxygen

Table 2 EA2, EA3: Land and surface water in Denmark

Forest	Unaffected	km^2
	Cultivated	km^2
Other terrestrial nature	Moor	km^2
	Meadow	km^2
	Bog	km^2
Agriculture	Ecological	km^2
	Conventional	km^2
Waterbodies	Groundwater	km^3
	Lakes	km^2
	Streams	km
	Tidal area	km^2
	Inlets and coastal	km^2
	Ocean	km^2

Resources can be divided into non-renewable resources (fossil fuels and minerals) and renewable resources (biotic resources, water, nitrogen, oxygen). The distinction between renewable and non-renewable resources is a matter of time perspective. In a very long time perspective – 500 millions of years – resources such as fossil fuels and minerals are renewable whereas flora and fauna are not renewable, but the distinction used in this paper, is that resources, which can be renewed by nature in less than 300 years are renewable. This means that some forests, trees, coral reefs and deep ground waters are non-renewable resources.

The amount of resources available to man (the reserves) can be defined as:

1 for renewable resources: nature's regeneration of new resources (t/year)

2 for non-renewable resources:

- Fossil fuels: those that can be exploited by today's available technology at a price less than three times the mean price of the last ten years.

- Scarce metals: the metals contained in ores in the outer earth crust, which can be exploited by today's available technology at a price three times the mean price of the last ten years. The total amount of metals existing in the ores is estimated at 400–2000 times the yearly exploitation amount today. The ores are of varying grade and copper and tin are among the scarce metals with lowest reserves of high-grade ores. Much higher amounts of metals exit scattered in the minerals outside the ores.
- Light metals: for aluminium and iron the resources are almost indefinite, since 8% of the earth crust consists of aluminium and 5% of iron.
- Non-metallic minerals: the metals contained in formations and ores in the outer earth crust. Phosphate is among the scarcest non-metallic mineral, since its highest grade is found as phosphorit, which is accumulated from dead animals. Resources of other non-metallic minerals are almost endless such as granite stone, sand and gravel.

3 Effects on environment and health

To delimit those material flows which have an essential impact on environment and health, it is useful to start with the concept of sustainable development. Focusing on welfare, health and environment the following criteria for sustainability can be posed:

Criteria for welfare:

A) The basic needs for food, clean drinking water, housing, clothes, education and social relations shall be met for every human being, and poverty is unacceptable. Nevertheless wealth is today unevenly distributed globally with among 1.2 billion people earning less than 1 $ per day in 1998 as estimated by the World Bank (2000)

Criteria for health:

B) Every human being has the right to a healthy life, which means hygienic, safe surroundings, healthy food, healthy housing, and access to healthcare and medicine.

Criteria for environment:

Emissions:

C) The ecological space (carrying capacity) for emissions into nature must not be exceeded. The ecological space for emissions can be defined as the emissions, which nature can convert and which do not change the quality of nature to an unacceptable degree.

Non- renewable resources:

D) The ecological space for non-renewable resources must not be exceeded.
The exploitation of non-renewable resources shall be less than or equal to new resources, which can be exploited by to day's available technology and prices.

Renewable resources:

E) The ecological space for renewable resources must not be exceeded. The exploitation of renewable resources shall be less than or equal to nature's regeneration of new resources. Renewable resources shall be protected against pollution, destruction and fragmentation (to such a degree that their capacity of regenerating non-polluted renewable resources is not reduced)

Parts of nature, resources or ecosystems, which are severely threatened, exploited or polluted beyond the carrying capacity of nature are (the criteria A-D are in brackets):

- the atmosphere in relation to temperature, climate and ozone layer depletion (A, B, E)
- air quality in cities (B, E)
- biodiversity (D)
- forests, especially unaffected forest and rainforest (A, B, C, D, E)
- other terrestrial parts of unaffected nature (A, B, C, D, E)
- fertile areas, which are threatened by erosion or desertification (A, B, C, D, E)
- oil and gas fields (A, B, D)
- precious metals (A, B, D)
- freshwater for supply of households, industry and agriculture (A, B, C, E)
- waterbodies: lakes, streams, rivers, coastal zones, ocean (A, B, C, E)
- fish stocks (A, B, C, E)

It appears from this that the same parts of nature are both essential for welfare, health, resources and emissions (recipients). Really the interactions between man and nature are extremely complex and demand a huge scientific effort to search out the interlinkage between material flows and their manyfold impacts on the environment and health. The influence of material flows on environment and health can be evaluated by a risk assessment. The risk is defined as the probability of the incident occurring multiplied by the consequences of the incident [17]. The consequences of material flows on the environment and health can be calculated as the number of deaths, cases of illness, epidemics, refugees, number of impoverished, loss of biodiversity, loss of unaffected nature, eutrophication of waterbodies, climate change, ozone layer depletion etc. According to the concept of sustainable development the consequences are estimated for many future generations. The longer the projection period into the future, the greater the uncertainty – which is a well-known result of chaos-theory. The time perspective – dependent on the type of consequence – should be about 500 years from now.

The precautionary principle must be used. If the consequences of a material flow or depletion of a natural resource are partly unknown, life and the environment shall benefit from the uncertainty.

It is important to assess:

- the possibilities of reducing the harmful material-flows and over what time period
- the relationship of cause and effect and the probability of the relationship

The relationship of cause and effect is not an easy issue in sustainability research due to the complexity of the dynamic systems involved. Since the uncertainty limits predictability, the precautionary principle is all the more important. It is also important to evaluate if the consequences are reversible or irreversible. Irreversible consequences are more severe than reversible consequences. In this context irreversible changes are not strictly thermodynamically understood, but should be understood as changes, which humanity is not able to reverse, for example, 1) recollect toxic substances, which are dispersed into nature, or 2) re-establish ocean-flows or 3) recreate species, which have been eliminated.

The consequences of the material flows and degradation of resources can be evaluated in relation to the carrying capacity of nature. The load, which is equal to the carrying capacity of nature, is often called the ecological space. The more the carrying capacity or the ecological space is exceeded the more nature is affected. The more nature is affected the greater are the consequences in the risk assessment. Therefore in a risk assesment an investigation of the material flows and resource degradation, compared to the carrying capacity, is essential.

In Table 3 examples of the impact of resource use and material flows on the environment and health are shown:

Table 3 Resources and material flows and their impact on environment and health

Resources		*Environmental effects*	*Health effects*
Coal	N	Greenhouse gases (CO_2, CO, CH_4) Air pollution (particles) Acidification (SO_2, NO_xér) Eutrophication (NO_xér)	Respiratory illness Diseases caused by climate change Hunger, water shortage
Oil	N		
Gas	N		
Uranium	N	Radioactive waste	Cancer, radiation sickness
Plutonium	N		
Mercury	N	Accumulating in the food chain Attacks organs and nervous systems in animals	Influence on organs: brain, nervous system, kidney, liver, sex organs
Cadmium	N		
Copper	N		
Chromium	N		
Nickel	N		
Tin	N		
Lead	N		
Aluminium	N	Energy consumption during extraction	
Iron	N		
Phosphorus	N	Eutrophication	Poisoning algae
Nitrogen	R	Eutrophication NO_3 in groundwater	Poisoning algae Cancer, 'blue' children
Precious timber	RN	Destruction of rainforest	Vital necessity for aboriginal
Biodiversity	RN	Reduction of Biodiversity	Reduction of genes for medicine, fibres etc
Synthesised dangerous chemicals		Toxic, endocrine, persistent and bioaccumulating.	Cancer, allergies, organ damage, hormone disturbance

Note: R: Renewable. N: Non-renewable.

The material flows, which have the most severe impact on environment and health in Denmark, are delimited by a risk assessment:

- fossil fuels
- heavy metals
- dangerous chemical substances
- nitrogen compounds

Land use can also have major impact on environment and health [18] because of the degradation of ecosystems and reduction of biodiversity

3.1 Fossil fuels

IEA [19] extrapolated the world's use of fossil fuels and found that CO_2 emissions will increase by 70% in the period 2000–2030. Increasing emissions of CO_2 will cause increasing concentrations of CO_2 in the atmosphere.

The probability that the increasing concentration of greenhouse gases will cause rising global temperatures is very high. The UN Climate Panel [20] assesses the probability at 90–99%. If the global mean temperature is increasing it is very likely that global waterflows in oceans, airflows in the atmosphere and precipitation will change [20]. Rising temperatures and changing precipitation and flows in the oceans and the atmosphere will very probably cause climate changes [20,22]. Changes will cause droughts, rising water levels, melting of the ice at the poles and in the high mountains[20], spreading of diseases, and migration [21]. The number of people suffering cases of illness and death will very probably be huge [21,22]. Climate changes and changes in flows of oceans are partly irreversible [20]. If the Gulf Stream is changing it is doubtful if it can be brought back to its original flow [21]. The Gulf Stream is stabilising the climate in Europe and a change will jeopardise Europe. Since the probability for climate change is high and the consequences are enormous and partly irreversible, the reduction of the emission of greenhouse gases must be the highest priority.

Though Danish central powerplants treat combustion gases for particles, sulphur and nitrogen compounds, the combustion of fossil fuels also causes the following severe impacts on environment and health:

- eutrophication of waterbodies reducing biodiversity and causing oxygen depletion and destruction of waterlife
- acidification of forests, waterbodies and buildings
- small particles, which cause respiratory diseases
- dispersion of heavy metals from combustion gases, fly ash and slag
- large quantities of slag and fly ash

The exhaustion period for Danish oil and gas resources is estimated to about 30 years. Since there will be no Danish oil and gas resources for the next generations, the carrying capacity for resources is exceeded on a national level. Global oil and gas resources are estimated at 50 years, which also tells us that the carrying capacity is exceeded, since there will globally not be enough oil and gas resources for the next generations.

Energy savings and renewable energy sources are therefore essential for sustainable development.

3.2 Heavy metals

Heavy metals dispersed into nature can be bio-accumulated in the food chain. By the process of bioaccumulation animals and humans can accumulate high concentrations of heavy metals, which cause severe sickness in the nervous system, brain, blood, skin and other organs. The dispersion of heavy metals into nature is irreversible: those elements can never be returned. The ecological space is exceeded for most of the heavy metals, since many animals have accumulated such high concentrations of heavy metals in their tissues that their health and reproduction capacity is harmed. In particular, animals and humans living in the Arctic and humans living in polluted cities have high concentrations of heavy metals in their bodies. In many countries pregnant women and children are asked not to eat too much fish because of the health risk – although unpolluted fish is very healthy. Some of the heavy metals have a relatively short supply-horizon: tin, around 20 years and copper, around 30 years as reported by The World Watch Institute [23]. Minimising losses, resource efficiency in production and use, substitution of heavy metals by harmless substances, enhanced reuse and longer lifetime for heavy metal containing products are necessary.

3.3 Dangerous chemicals

Still more dangerous chemicals are developed, produced, used and dispersed into nature, and the authorities are not able to assess, classify and regulate all these new substances. In Denmark and the EU around 30,000 different chemicals are in use. The risks of these chemicals differ and only a few, until now, have been assessed for risk by the EU. The slowly biodegradable and bioaccumulating chemicals will be accumulated in the food chain. By this process mammals and humans accumulate a mixed cocktail of unhealthy substances. Dangerous chemicals can cause cancers, allergies, hormonal disorders, nerve and brain conditions, reduced reproductive capacity, and deformed babies. The dispersion of these substances in nature is irreversible, since they can never be recalled. Thus, since the consequences for the environment and health are severe and the dispersion is irreversible, the reduction of dangerous chemical production and emissions must have a very high priority.

3.4 Nitrogen compounds

Emission of nitrogen compounds causes:

- eutrophication of inlets, coastal zones and oceans
- percolation of nitrates into groundwaters

The sources of nitrogen emission are agriculture and combustion processes. Also wastewater is a source of nitrogen, but in Denmark nitrogen is removed from most wastewater. Most nitrogen comes from agriculture from the use of fertilisers and manure. In Denmark groundwater is the source of all water supply. Nitrate concentrations in Danish groundwater are increasing and more and more wells have water with nitrate concentrations exceeding WHO health limits. Too high a human intake of nitrate causes cancer in the stomach and the blood disease called 'blue babies'.

Eutrophication of the inlets and coastal zones causes oxygen depletion and more frequent widespread killing of life in coastal zones and hydrogen sulphide formation. The ecological space for emission of nitrogen to surface water and groundwater is exceeded. The cause-effect relationship of nitrogen and eutrophication/nitrate in groundwater is scientifically established. And since the consequences of nitrogen emission are severe to both environment and health, reductions in nitrogen emissions must have a high priority.

3.5 Degradation of ecosystems and reduction of biodiversity

Globally human beings confiscate more and more natural areas for their needs, which causes tremendous destruction and reduction of the ecosystems and biodiversity. Cutting down, fragmentation and cultivating of forests destroys the forest ecosystem, reduces biodiversity, increases the risk of floods and reduces the uptake of greenhouse gases. Transforming natural ecosystems into agricultural areas causes pollution of the groundwater with nitrates and pesticides, eutrophication of the lakes, the inlets and the sea, turns the natural watercourses into channels and increases the risk of flood and erosion. Fragmenting the ecosystems by roads and railways reduces the biodiversity. In Denmark, natural ecosystems and biodiversity have been seriously affected and reduced during two periods over the last 2,000 years. Firstly, transforming forests into medieval agricultural systems, and secondly, transforming medieval agriculture into industrialised agriculture through the use of pesticides and fertilisers, and transforming handcrafts into an energy intensive industrial society based on fossil fuels. Thus in Denmark the ecological space for ecosystems and biodiversity has been over-exploited. The remaining natural ecosystems are limited in scale and too much land is used for agriculture and involves the use of pesticides and nitrogen.

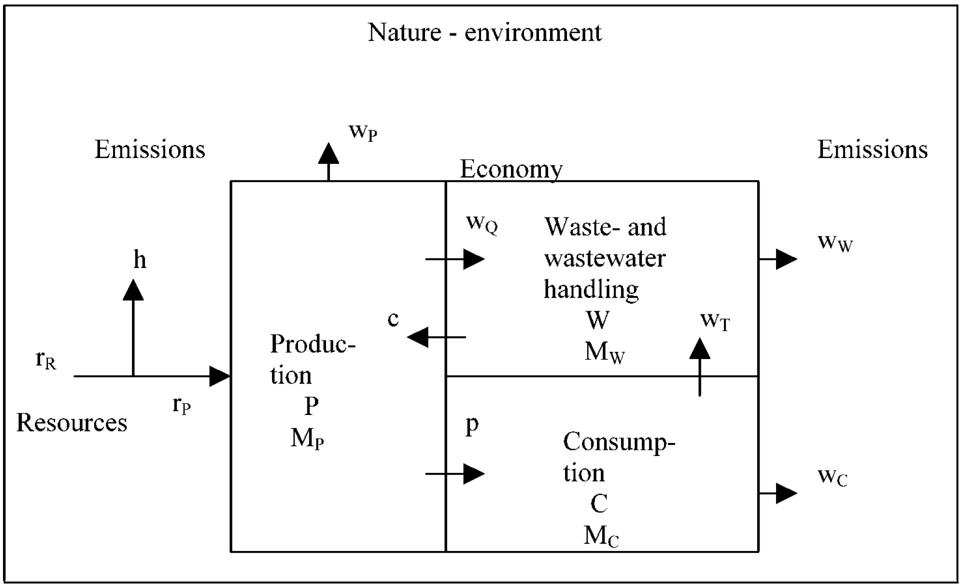
4 Model for material flows

In Figure 1 a model for material flows in a global or national economy (without import and export) is shown:

The economy is divided into three sectors: production (P), consumption (C) and water and wastewater treatment (W). Those materials, which are accumulated in each sector of the economy are symbolised by 'M' with an index, which symbolises the sector:

M_P: materials in the production sector (tons)
M_C: materials in the consumption sector (tons)
M_W: materials in the waste and wastewater treatment sector (tons)
Δ : the yearly accumulated materials in the sectors (t/year).

Figure 1 Model for national or global material flow



Resources, products, waste:

- r_R: resource extraction from nature (t/y)
- r_P: resources into the production sector (t/y)
- p: products produced (t/y)
- w_T: waste and wastewater from consumption sector into the treatment sector (t/y)
- w_Q: waste and wastewater from production sector into the treatment sector (t/y)
- c: recirculated materials from the waste and wastewater sector to the production sector (t/y)

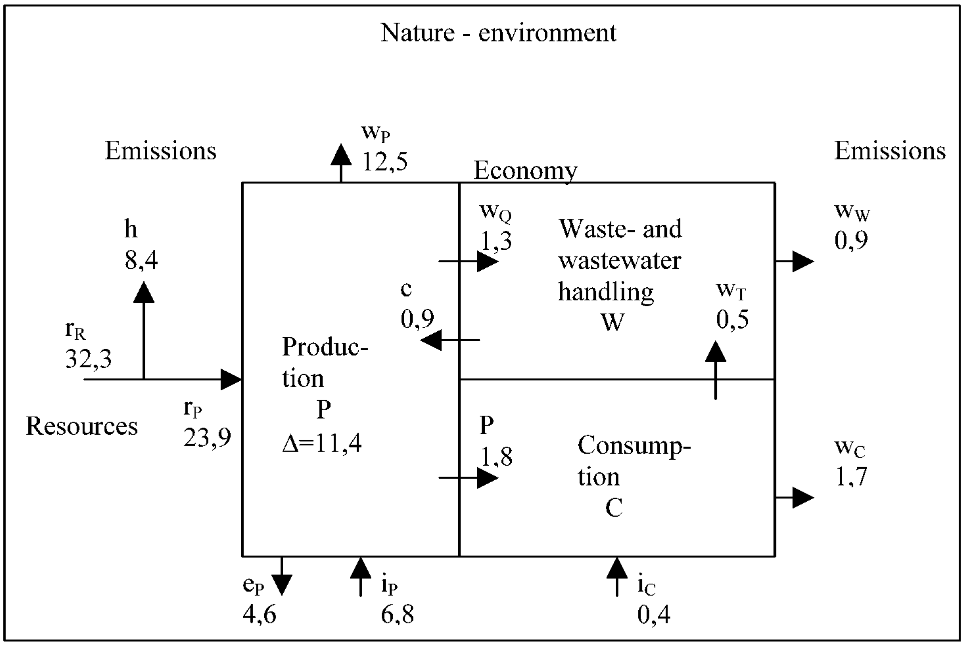
Emissions:

- h: unused (or hidden) flows from resource extraction (t/year)
- w_p: emissions from production to nature (t/year)
- w_C: emissions from consumption to nature (t/year)

The sector of waste-and wastewater treatment also uses energy and materials from the production sector, but these are relatively small and are neglected, so as not to lose simplicity. All these variables are time-dependent. Each material flow in Figure 1 can be divided into three flows according to its state: solid, liquid and gas. Also the material flows can be divided and marked according to which resource they originate from. The model is defined in flows and masses but can also be used for flows per person and mass per person by dividing all flows and masses by world population or number of inhabitants per nation. If the model is defined as per person, the variables can be defined as a statistical distribution and thereby, for example, can reveal which part of the population is using most resources.

Expanding the model in Figure 1 with imports and exports and assuming that no waste is traded; yields the model in Figure 2:

Figure 2 Model for national economy with import and export (tons/person/year for Denmark 1990)



where:

e_P: export from production sector
i_P: import to production sector
i_C: import to consumption sector

In Figure 2 the total Danish material-flows are shown measured in tons/person/year for 1990. Water used for products (0.6 t/per/year) and water contained in products and waste are included. In Danish input-output tables all building and construction are investments allocated to the production sector. Data from Danish input-output tables [9] and the Danish Waste Statistics, ISAG, were used.

Figure 2 shows:

- that a relatively small material flow for consumption implies large material flows for resource extraction and consumption
- that total emissions are 15 times greater than the material flow for consumption
- that total emissions are 18 times greater than the collected waste and substances in wastewater – thus the collected waste is only 'the tip of the iceberg'
- that the mean degree of recirculation of waste is about 50%.

The corresponding MFA indicators for 1990 were: TMR = 66 t/per/y, TMC = 48 t/per/y, DMI = 31 t/per/y and DMC = 26 t/per/y [10]

The relations between MFA-indicators and the model in Figure 2 are:

Input:

$TMI = r_R + \sum i,$ $\quad r_R = TMI - \sum i$

$DMI = r_P + \sum i$ $\quad r_P = DMI - \sum i$

$DMC = r_P + \sum i - e_P$ $\quad r_P = DMC - \sum i + e_P$

Accumulation:

$NAS = \sum M$

Output:

$TMO = \sum w - e_P$ $\quad \sum w = TMO - e_P$

$TDO = \sum w$ $\quad \sum w = TDO$

$DPO = \sum w - h$ $\quad \sum w = DPO - h$

where:

$\Sigma i = i_P + i_C$

$\Sigma M = M_P + M_C + M_W$

$\Sigma w = w_P + w_C + w_W$

6 Resource efficiency

Resource efficiency can be defined as those resources that are used to meet the material needs of human beings. Resource efficiency can then be expressed as the relation between the material human needs and the resources used to meet the material needs:

$$\text{Resource-efficiency:} \quad \gamma = \frac{\text{needs}}{\text{resources}}$$

which is also called 'the productivity of resources'.

Resource efficiency can be defined as resources related to economic turnover, area or service units. Defining resource efficiency in purely physical terms and in terms of material flows gives:

Human needs can be approximated by the products, which are used to meet the needs. This is a rough approximation, since needs are often not met by the products consumed. Thus the resource-efficiency can be defined as:

$$\text{Resource-efficiency:} \quad \gamma = \frac{p}{r}$$

where:

p: material flow from production sector into consumption sector

r: material flow of resources

The resources can be either resources exclusive or inclusive unused flows during resource extraction:

Resource efficiency excluding unused flows: $\gamma_P = \frac{p}{r_P}$

Resource efficiency including unused flows: $\gamma_B = \frac{p}{r_R}$

In Table 4 expressions for resource efficiency for each sector of society and for the whole society are shown:

Table 4 Resource efficiency for a closed economy without import and export

	Resource efficiency γ		
Resource extraction	γ_R	$\frac{r_P}{r_R}$	$\frac{\text{Resources into production}}{\text{resource extraction}}$
Production	γ_P	$\frac{p}{r_P}$	$\frac{\text{Products into consumption}}{\text{resources into production}}$
Consumption	γ_C	$\frac{p}{w_C}$	$\frac{\text{Products into consumption}}{\text{emissions from consumption}}$
Waste-and wastewater treatment	γ_W	$\frac{c}{w_T+w_Q}$	$\frac{\text{Recirculated waste}}{\text{Waste and wastewater for treatment}}$
Total incl. unused flows	γ_B	$\frac{p}{r_R}$	$\frac{\text{Products into consumption}}{\text{resource extraction}}$
Total after resource extraction	$\gamma_N = \gamma_P$	$\frac{p}{r_P}$	$\frac{\text{Products into consumption}}{\text{resources into production}}$

Flows of resources as well as flows of products can be split into different flows, which affect environment and health. Splitting into flows of energy, water, dangerous chemicals and heavy metals we obtain the following matrix for resource efficiency, $\gamma_{i,j}$:

Energy efficiency:

$\gamma_{ep} = p/r_{energy}$, $\gamma_{er} = p_{energy}/r$ $\gamma_{ee} = p_{energy}/r_{energy}$

Water efficiency:

$\gamma_{qp} = p/r_{water}$ $\gamma_{qr} = p_{water}/r$ $\gamma_{qq} = p_{water}/r_{water}$

Use of toxic chemicals:

$\gamma_{tp} = p/r_{toxic\ chemica}$ $\gamma_{tr} = p_{toxic\ chemicals}/r$ $\gamma_{tt} = p_{toxic\ chemicals}/r_{toxic\ chemicals}$

Use of heavy metals:

$\gamma_{hp} = p/r_{heavy\ metals}$ $\gamma_{hr} = p_{heavy\ metals}/r$ $\gamma_{hh} = p_{heavy\ metals}/r_{heavy\ metals}$

The resource flow for toxic chemicals is the resource flow of virgin synthesised toxic chemicals.

Often the reciprocal value, κ, product efficiency – is used instead of, γ:

Product *efficiency*: κ = 1/γ = resource/product

which is also called the 'resource intensity of production'. For example: Product efficiency for water:

κ_q = water – use/product

In the context of the DPSIR-model the resource efficiency, γ, is the relation between the flow of products, p, in the 'Driving Force'-category and the resource flow, r, in the 'Pressure'-category.

Resource efficiency, γ, can also be expressed as a function of the emissions, w, and resource use, r. At stationary conditions (no accumulation):

$$\gamma = \frac{\text{product}}{\text{resource}} = \frac{p}{r} = 1 \div \frac{w}{r}$$

where w = emissions from production.

At dynamic conditions (with accumulation Δ in production):

$$\gamma = \frac{p}{r} = 1 \div \left(\frac{(w+\Delta)}{r} \right)$$

Resource efficiency, γ, have values of all positive real numbers: ∞ ≥ γ ≥ 0.

Resource efficiency can be greater than '1', if materials are recirculated back to production. If all resources are recirculated and reused, or lifetime is infinite long, or emissions are zero, resource efficiency will be infinite great. Thus resource efficiency, γ, is rather sensitive at high efficiency but only a little sensitive at small efficiency.

Including import and export, Figure 2, in the expressions for resource efficiency:

Resource efficiency excluding unused flows:

$$\gamma_P = \frac{p + i_C}{r_P - \eta e_P + \varphi(i_P + i_C)}$$

Resource efficiency including unused flows:

$$\gamma_B = \frac{p + i_C}{r_R \left(1 - \frac{\eta e_P}{r_P} \right) + \varepsilon j(i_P + i_C)}$$

where:

- φ: mean IF-factor for emissions from production of imported goods abroad
- η: mean IF-factor for emissions from production of exports in Denmark
- ε: mean IF-factor for unused resources during resource extraction abroad

Resource efficiency for a whole nation inclusive of imports and exports also can be expressed by a combination of the model in Figure 2 and MFA-indicators:

Resource efficiency exclusive unused flows:

$$\gamma_P = \frac{p + i_C}{DMI - \eta e_P + (i_P + i_C)(j - 1)}$$

Resource efficiency inclusive unused flows:

$$\gamma_B = \frac{p + i_C}{TMR - \eta e_P \frac{r_R}{r_P}} = \frac{p + i_c}{TMC}$$

Other measures of resource efficiency are *intensities*, which are resources or products flows divided by:

- economic turnover (tons/GDP) which is called economic resource intensity, for example: fossil fuels used per GDP
- service-unit (tons/service-unit), service-unit intensity (MIPS) for example material use per person transported per year
- area (tons/(area × year), which is called area resource intensity, for example tons pesticides used per ha per year
- per person (tons/person × year), per person resource intensity, for example tons fossil fuels used per person per year.

Decreasing economic resource intensity is also called economic decoupling and shows to what degree economic growth is decoupled from resource use. Material flows per service unit (MIPS) are the closest measure to the definition of resource efficiency, since it measures resource use in relation to human services. Although MIPS are very useful at the product and unit service level, it is difficult to do aggregated MIPS calculations for a whole national economy. Area resource intensity expresses how much an area is loaded by material flows. Material flow per person is not really an efficiency measure, but a measure of how much material one person in average is turning over.

Other measures for efficiency are:

- resource productivity (GDP/tons) or eco-efficiency, which is the reciprocal value of economic resource intensity
- percentage or part of, for example percentage of dangerous chemicals in products, which ends up in the waste or percentage renewable energy of total energy

These indicators express a relation between two variables in different categories of the DPSIR-model. For example, the resource-intensity (r/GDP) expresses the relation between the resource-flow in the 'pressure' category and the gross national economic turnover in the 'Driving force'-category.

7 Lifetime

Lifetime, T, for materials in a sector of society is defined as the amount of materials stored in the sector, M, divided by the outgoing material flows from the sector, m. For stationary conditions we obtain:

$$T = \frac{M}{m}$$

For dynamic conditions the lifetime is found by integration over the whole lifetime of the mass flow:

$$T = \frac{1}{T_m} \int_0^T \frac{M(t)}{m(t)} d(t)$$

Where T_m: mean lifetime

Lifetime for materials can be calculated for each sector of society as well as for the whole of society (see Table 5 for stationary conditions):

Table 5 Lifetime for stationary conditions

Sector		*Lifetime T*	
Production	TP	$\frac{M_P}{p + w_P + w_Q}$	$\frac{\text{Materials in production-sector}}{\text{Products + emissions + waste for treatment}}$
Consumption	TC	$\frac{M_C}{w_T + w_C}$	$\frac{\text{Materials in consumption-sector}}{\text{Waste for treatment + emissions}}$
Waste and wastewater treatment	TW	$\frac{M_W}{c + w_W}$	$\frac{\text{Materials in waste-and wastewater treatment}}{\text{Recirculated materials + emissions}}$
Total incl. unused flows	TΣ	$\frac{\Sigma_M}{h + w_P + w_C + w_W}$	$\frac{\text{All materials in society}}{\text{All emissions}}$
Total after resource extraction	TN	$\frac{M_P + M_C + M_W}{w_P + w_C + w_W}$	$\frac{\text{Materials in production, consumption and treatment sectors}}{\text{Emissions from production, consumption and treatment-sectors}}$

For example the lifetime (years) for building materials in the consumption sector is the materials of all living houses (tons) divided by the demolition rate (tons/year).

8 Proposal for indicators

In this context, indicators should show if the material flows approximate sustainable development. The value of the indicator can be compared to the politically defined target of sustainable development and the distance to target can be calculated. This distance to target can be used to decide politically the appropriate regulation of the economy, resource exploitation and the emissions, to minimise the distance to target. Hereby the indicator becomes the output signal in a regulation circuit to decide the error (distance to target) and to optimise the regulation of the system.

Demands must be made on the indicators for their relevance, quality, methods of measurement, validity, uncertainty, precision, comparability, understandability, data accessibility and frequency. It is recommended to use the methodology proposed by the UN [11] modified for use at national level:

1 Indicator: name, definition, unit of measurement, placement in the Indicator Set

2 Policy relevance: purpose, relevance to sustainable development, international conventions and agreements, international and national targets, links to other indicators

3 Methodological description: underlying definitions and concepts, measurement methods, limitations of the indicator, status of the methodology, alternative definitions/indicators

4 Assessment of data: data needed to compile the indicator, national and international data availability and sources, data references.

5 Agencies involved in the development of the indicator, other contributing organisations

6 References: readings, internet sites

For the future choice of indicators for EU countries, such indicators should be chosen, which are recommended by the UN, OECD and EU to compare national figures with international figures. Additionally specific national indicators should be chosen to supplement the international indicators.

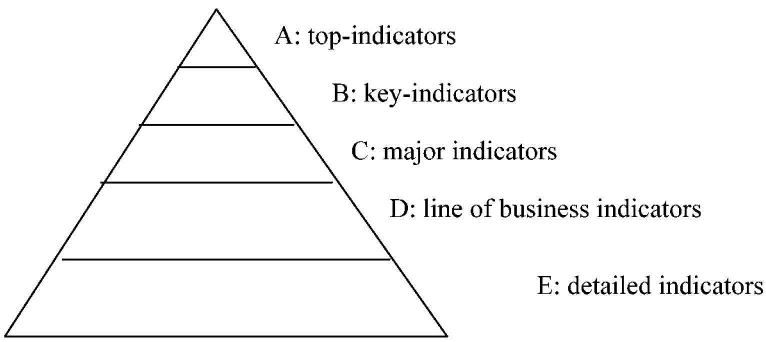
It is recommended to use the classification of resources, which is proposed by the UN in the SEEA 2000 system. It is also recommended to put material flows in relation to:

- number of inhabitants: world population or national population
- the economic turnover such as BFI, BNI or BFI

It is further recommended to structure the indicator-system as an indicator-pyramid, see Figure 3.

At the top of the pyramid are a small number of indicators for the material flows, energy flows and area use, which have the most severe influence on environment and health. At the bottom of the pyramid are a huge number of indicators for specific material flows in specific lines of business.

Figure 3 Indicator pyramid



The indicator pyramid can be further structured by a formal indicator system according to the mathematical model in Figure 1 and Figure 2, the definitions of resource efficiency and lifetime and the use of area. The formal indicator-system is shown in Table 6 with the following symbols:

r: resource flows
w: sum of emissions
p: flow of products
c: recirculation into production
M: amount of materials in consumption sector
e_r: ecological space for resources
e_e: ecological space for emissions
BFI: gross factor income
N: number of inhabitants
K: total capital (floating plus fixed)

Resources can be calculated before and after resource extraction. If resources are calculated before resource extraction, the sum of emissions must include unused flows.

Plus indicators for *use of area*, A, as proposed by J. Spangenberg [4]:

1 city, houses, transport, consolidated area, A_c

2 conventional agriculture, A_a

3 ecological agriculture, meadow and cultivated forest, A_f

4 unaffected nature, A_n

The changes by time of the indicators will be added as derived indicators. Hereby rises or falls of the indicators and the speed of change are shown. Thus it can be verified if the indicator is approaching the target and if the speed of the approach is as desired. Concrete indicators organised by the levels of the indicator pyramid, Figure 3, and the formal indicator system, Table 6, are proposed for Denmark in Table 7:

Table 6 Formal indicator system

		Material-flows, efficiency, lifetime	*Pressure on ecological space and welfare*	*Resource-intensity,*	*Per inhabitant*
Resources	r	r	$\frac{r}{e_r}$	$\frac{r}{BFI}$	$\frac{r}{N}$
Emissions	w	w	$\frac{w}{e_e}$	$\frac{w}{BFI}$	$\frac{w}{N}$
Resource-efficiency	γ	$\frac{p}{r}$			
Lifetime	T	$\frac{M}{p}$			
Reuse relation	β	$\frac{c}{w}$			
Material welfare	M	M	$\frac{MSL_{min}}{\gamma_p \times T_C \times r}$	$\frac{M}{K}$	$\frac{M}{N}$

Table 7 Proposal for indicators in the indicator pyramid

A. Top indicators 4			*B. Key indicators 15*	*C. Major flow and area indicators 44*
Name	*Symb.*	*Unit*	*Name*	*Name*
Aggreg.material consumption	TMR	t/per/y	DMI	Biomass, minerals, f.fuels
			TMC	Biomass, minerals, f.fuels
			NAS	Biomass, minerals, f.fuels
			TMO	Biomass, minerals, f.fuels
Total primary energy consumption	PEC	J/per/y	Fossil fuels	Coal
				Oil
				Gas
			Renewable energy	Sun
				Wind
				Water
				Underground
				Biomass
			Nuclear energy	High risk
				Low risk
Area of almost unaffected nature	A_n/A	%	Almost unaffected nature	Forest
				Meadows
				Bogs
			Almost unaffected land	Cultivated forest
				Meadows and bogs
				Ecological agriculture
			Almost unaffected inlets and coastal zones	Lakes
				Streams
				Tidal waters
				Coastal zones
Dangerous flow consumption	DFC	g/per/y	Dangerous chemicals	High risk
				Medium risk
				Low risk
			Heavy metals	High risk (Hg, Cd)
				Medium risk (Ni, Pb, Cr)
				Low risk (Cu, Zn)
			Radioactive substances	High risk
				Low risk
			Water con-sumption	By households
				By enterprises
			Nitrogen consumption	Extracted indust. from air
				Extracted biolog. from air

The indicators in the upper levels, A, B and C, are indicators for aggregated and disaggregated material consumption, energy consumption and area use, which were delimited by the risk assessment and the exceeding of the ecological space

The indicators in the lower levels of the indicator pyramid are:

- level 'D': indicators for lines of business structured by the formal indicator system,Table 6
- level 'E': indicators for specific material flows in specific lines of business structured by the formal indicator system, Table 6

The indicator system in Table 7 can also be used for other countries, if some of the indicators are replaced into a higher or lower level, depending on which environmental problems are most severe in the specific country. For arid countries water consumption should be in level 'A' instead of in level 'B'.

9 The path to sustainable development

The criteria for sustainable development can be formally expressed:

C) Criteria for emissions: Emissions, w, shall be less than or equal to the ecological space for emissions, e_e:

$$w \leq e_e \Leftrightarrow w/e_e \leq 1.$$

'w/e_e' is the pressure of emissions on the ecological space for emissions

and by differentiating: $\delta w \leq \delta e_e$

which express the alarming *double speed of unsustainable development* because δe_e is often negative due to the reduction of the quality and size of ecosystems and δw is often positive due to increasing emissions. This is especially alarming in relation to the greenhouse effect: reducing CO_2 uptake due to reduction of terrestical plant chlorophyll area combined with increasing emissions of CO_2, will cause increasing concentration of CO_2 in the atmosphere.

D and E) Criteria for resources: Resource exploitation, r, shall be less than or equal to the ecological space for resources, e_r (= exploration of new non-renewable resources or regeneration of renewable resources):

$$r \leq e_r \Leftrightarrow r/e_r \leq 1.$$

'r/e_r' is the pressure of resources on the ecological space for resources.

and by differentiating: $\delta r \leq \delta e_r$

which shows the *double speed of unsustainable development* for some renewable resources such as, fish, tropical timber and slow regenerating groundwater. The regeneration of those renewable resources is reduced because of pollution, defragmentation or destruction, whereas the exploitation of these resources is increased. For non-renewable resources δe_r is close to zero, because of the emptying of easy available resources of high grades, whereas δr is increasing because of increased consumption of non-renewable resources.

A) Criteria for welfare: The products for use, M_C, shall be greater than or equal to the political decided minimum material standard of living, MSL_{min}:

$$M_C \geq MSL_{min}$$

Since $M_C = p \times T_C$ and $\gamma_P = p/r$:

$$p \times T_C \geq MSL_{min} \Leftrightarrow$$

$$MSL_{min}/(p \times T_C) \leq 1 \Leftrightarrow$$

$$MSL_{min}/(\gamma_P \times r \times T_C) \leq 1.$$

'$MSL_{min}/(\gamma_P \times r \times T_C)$' is the pressure on welfare

and by differentiating:

$$\delta MSL_{min} \leq \delta M_C \Leftrightarrow$$

$$\delta MSL_{min} \leq (\gamma_P\, r\, \delta T_C + T_C \gamma_P\, \delta r + T_C r\, \delta\gamma_P)$$

which tells us, that to eliminate global material poverty and increase the global material standard of living, the sum of multiplicates of resource efficiency, lifetime of products and resource extraction has to increase.

Combining the criteria A), C), D) and E) we find the sustainability criteria for both material welfare and environment:

$$\frac{MSL_{min}}{\gamma_P \times T_C} \leq r \leq e_r \wedge r = w \leq e_e$$

(if no stock addition is assumed) or:

$$\frac{MSL_{min}}{\gamma_P \times T_C} \leq r \leq e \text{ where } e = \min(e_r, e_e)$$

telling us that the consumption of resources shall be greater than or equal to the need for material welfare and less than or equal to the environmental space for both resources and emissions. This is also called the floor and ceiling of sustainability for material welfare and environment. The combined criteria also tells us that the path to sustainability goes through increasing resource efficiency, γ, increasing lifetime of products, T, and dematerialisation of welfare, MSL.

Differentiating we obtain:

$$\delta MSL_{min} \leq (\gamma_P r \delta T_C + T_C \gamma_P \delta r + T_C r \delta\gamma_P) \leq (\gamma_P e \delta T_C + T_C \gamma_P \delta e + T_C e \delta\gamma_P)$$

which shows the differential narrow path to sustainability through increasing resource efficiency, $\delta\gamma$, increasing lifetime of products, δT, increasing quality and quantity of natural ecosystems, δe, and dematerialisation of welfare, δMSL.

10 Examples of calculating resource efficiency

Indicators for total material-flows in Denmark 1990 are calculated from Figure 2:

The IF-factors are estimated:

$\eta = 2$

$\varphi = 2{,}2$

$\varepsilon = 2$

Resource efficiency exclusive unused flows:

$$\gamma_P = \frac{p + i_C}{r_P - \eta e_P + \varphi(i_P + i_C)} = \frac{1{,}8 + 0{,}4}{23{,}9 - 2 \times 4{,}6 + 2{,}2(6{,}8 + 0{,}4)} = 0{,}07$$

Resource efficiency inclusive unused flows:

$$\gamma_B = \frac{p + i_C}{r_R\left(1 - \frac{\eta e_P}{r_P}\right) + \varepsilon j(i_P + i_C)} = \frac{1{,}8 + 0{,}4}{32{,}3\left(1 - \frac{2 \times 4{,}6}{23{,}9}\right) + 2 \times 2{,}2(6{,}8 + 0{,}4)} = 0{,}04$$

To increase resource efficiency in Denmark it is most important to reduce consumption of fossil fuels and material use for construction and building.

Examples of calculating indicators for resource efficiency in level D in the indicator pyramid are shown for the furniture line of business in Denmark:

For *the furniture line of business itself* in Denmark exclusive unused flows and recirculation, data from Kirsten Pommer (2002) [24] are used:

Resource efficiency is calculated as the overall *material efficiency,* γ_{mP} for the furniture line of business by using tons total aggregated flows (1000 tons):

$$\gamma_{mP} = \frac{p}{r_P} = \left(\frac{\text{furnitureproduction}}{\text{resourceuse}}\right) = \frac{385}{940} = 0{,}41$$

As an alternative resource efficiency, γ_{mP} ,for the furniture line of business can be calculated by the emissions instead of by the products:

$$\gamma_{mP} = 1 + \left(\frac{\text{reuse-emissions-accumul}}{\text{resourceuse}}\right) = 1 + \frac{28\text{-}531\text{-}0}{940} = 0{,}46$$

The difference between resource efficiency on 0,41 and 0,46 is caused by the inaccuracy of the data.

The *energy efficiency,* γ_{eP} in the furniture line of business itself (production-sector) is calculated:

$$\gamma_{eP} = \frac{p}{r} = \left(\frac{\text{Furnitureproduction}}{\text{energyuse}}\right) = \frac{385}{5{,}6+3{,}8} = 41$$

tons furniture/TJ.

For the whole lifecycle of furniture in Denmark inclusive resource extraction at home and abroad we obtain:

Overall material efficiency, γ_{mN} ,for total aggregated material flows:

$$\gamma_{mB} = \frac{p}{r_R} = \left(\frac{\text{Furniturproduction}}{\text{resourceuse in R,P,C og W sector}} \right) = \frac{385}{940 \times 3{,}7} = 0{,}11$$

Thus resource efficiency is much smaller for the whole life cycle (0,11) than for the furniture line of business itself (0,41). The reason why is primarily the material use and unused flows in resource extraction.

Calculating the energy efficiency for the whole life cycle:

$$\gamma_{eB} = \frac{p}{r} = \left(\frac{\text{Furnitureproduction}}{\text{energiuse} - \text{regaining}} \right) = \frac{385}{5{,}6 + 3{,}8 - 6{,}6} = 138$$

t furniture/TJ.

Thus energy efficiency is much greater for the whole life cycle (138 tons furniture/TJ) than for the furniture line of business itself (41 tons furniture/TJ). The reason is that the energy in the wood is regained by incineration of the furniture waste.

10 Conclusion

By means of a risk assessment and using the concept of ecological space the consumption of resource flows with the greatest impacts on environment and health in Denmark can be delimited to:

- fossil fuels
- heavy metals
- dangerous chemicals
- nitrogen compounds

Area use can be used as an indicator for ecosystems and biodiversity.

Resource efficiency can be defined in terms of material flows only, and can be calculated for the whole society with and without unused flows, each sector of the society and each line of business as well. By relating material flows to economic turnover, service units or number of inhabitants, other measures of efficiency can be defined.

An indicator system consisting of an indicator pyramid structured by formal indicators is recommended. At the top of the indicator pyramid are indicators for total aggregated material requirement, TMR, total primary energy consumption and the material flows and area use, which have the most severe impact on environment and health. At the bottom of the pyramid are indicators for specific material flows in specific lines of business. The formal indicators represent flows of resources and emissions, resources and emissions related to ecological space, economic turnover and number of inhabitants as well as resource efficiency, lifetime of materials and material welfare.

The path to sustainable development goes through dematerialisation, detoxification, increased resource efficiency and lifetime of products, protection of natural resources against pollution, defragmentation and destruction.

The resource efficiency for total material flows was calculated to 0.07 without unused flows and to 0.04 with unused flows for Denmark 1990.To increase resource efficiency and decrease emissions it is most important to reduce use of energy and fossil fuels and to reduce accumulation of materials in the technosphere.

For the furniture line of business in Denmark the resource efficiency for materials was calculated to be 0,41 for the furniture line of business itself, but 0,11 for the whole life cycles of furniture including unused flows during resource extraction. The energy efficiency was calculated to be 41 tons furniture/TJ for the furniture line of business itself but 138 t furniture/ TJ for the whole life cycle of furniture including regaining of energy by waste incineration.

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