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The sustainable process index (SPI): evaluating processes according to environmental compatibility

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Abstract

Process industry needs a strategic measure that takes environmental considerations into account as a base for decisions on future projects. Emission standards alone are not sufficient for this purpose. They are based on our knowledge of the environmental risk of substances which is fragmentary and inconclusive. On top of that emission standards are susceptible to changes in societal risk assessment. Both factors are changing rapidly undermining the usefulness of these standards for strategic planning. The SPI is based on an operationalized form of the principle of sustainability. It uses only process data known at an early stage of planning and data of natural concentrations of substances (not on their presumable impact which is usually not known). The core of the SPI evaluation is the calculation of the area needed to embed a process completely into the biosphere. Low SPI values indicate processes that are competitive under sustainable conditions and that are environmentally compatible in the long-term view.

1. Introduction

Strategic planning in process industry is very much concerned with ecological impacts. Pressure from society towards environmentally compatible processes is increasing which in turn causes industry to investigate new technologies as well as new ways to provide services. However, no universal measure is available to steer technological development in the right direction.

As a matter of fact we cannot trace a specific environmental effect in a mechanistic way. Neither can the ecosphere be seen as a machine nor did human engineers construct it. The ecosphere is so complex in its synergisms that we have (and always will have) to recognize our insufficient knowledge. We have to be aware of the fact that although we can ask the question of the appropriate carrying capacity we will never be able to answer it. The possible environmental burden and the limited capacity of the

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ecosphere are therefore an inappropriate basis for an ecological evaluation. As a logical consequence environmental management by human beings is impossible. Every disturbance of the immensely complex system of the earth results in unforeseeable effects [1]. That is why the evaluation of environmental burdens should only be based on the demand to minimize the environmental effect of mankind.

History has shown so far that there is no way to foresee which substances will become susceptible to ecological scrutiny. From CFCs over ozone to carbon dioxide there is a long list of substances which were not considered detrimental to the environment just years ago and which now require close monitoring or are phased out altogether. In spite of the large effort put into ecological toxicology our knowledge of the ecological function of certain substances is fragmentary at best and will certainly remain so in the years to come.

Another important aspect is that industry (and engineers as important actors in technological development) tend to separate their field of action from the environment.

So engineers are still used to a relatively narrow definition of 'process' (and of 'technology'). Usually, a process is defined as what goes on in a plant, limited by the physical installations of the plant. In this concept, engineers take responsibility for the safety within the plant and the quality of the products leaving it. The process is linked to the 'outside world' by authority regulations and, above all, prices for raw materials, labour, energy, waste and products.

This process model is highly insufficient for ecological process engineering. It separates the process from the environment and leaves evaluation and optimization of a process dependent on predominantly economic signals and on the principle of maximizing profit. In the same manner as prices fail to reflect environmental realities, processes fail to be ecologically safe.

Thus, ecological process engineering requires a radically new definition of 'process' (and with it 'technology') itself. A process has to be defined as providing a certain service, taking into account the whole chain from raw material generation, production and distribution to taking care of the products (which provide the service wanted) after their use and of the by-products (which are not wanted but have originated from the process). It is within this drastically enlarged process definition that evaluation has to take place (see Fig. 1).

By defining a process more widely and by including raw material generation, energy production, by-product treatment and recycling into the process, ecological process engineering can deal with process design and optimization much more consistently with respect to ecological problems, albeit at the cost of increased methodological complexness.

The enlargement of the process system is already an important improvement in the process engineering concept. However, it is not in itself the solution of the problem. As long as economic measures stay the only guideline, process industry will not be able to embed their activities into the environment with minimized ecological impact. Therefore, ecological process engineering has to rely on a new guideline. We propose the principle of sustainability to be this new guideline.

As traditional economic evaluation methods are not able to account for sustainability [2–4] and do not measure ecological aspects within the enlarged task of ecological

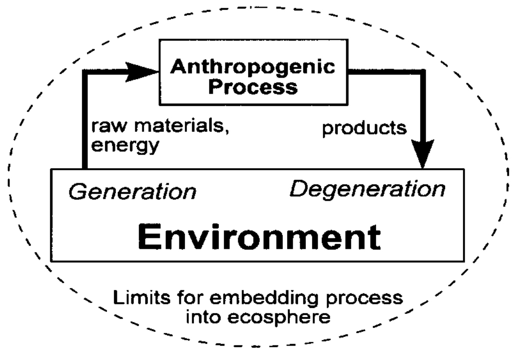

Fig. 1. New definition of a process.

process engineering, supplementary measures are necessary. This is especially important since today's technological decisions face (at least partly) new economic realities that come closer to the principle of sustainability. It is therefore important to create strategic measures which can evaluate the viability of processes under the new constraints of competition.

A number of interesting approaches to this problem already exist. For example, eco-balances [5, 6] are widely applied in order to relate flows to and from processes to ecologically critical flows. The degree of invasiveness of a technology can be evaluated [7]. The material intensity per unit-service evaluates the mass of material necessary to be moved in order to provide a certain service [8]. Other indicators and measures were suggested and tested [9–15] and sustainability standards were fixed [16] as well.

These methods, which are usually based on socially defined limits (e.g. emission or immission threshold values) cannot be integrated into engineering tasks which finally define the impacts of industrial metabolism. In contrast the sustainable process index (SPI) evaluates technical processes according to their competitiveness under completely sustainable conditions. It is based solely on data which are known at an early stage of planning. Therefore, it can be used for screening different process alternatives as well as different technological possibilities of supplying a necessary service.

2. Basic concept of the SPI

Any measure of sustainability must be based on an operationalized formulation of the concept.

Sustainability has been broadly discussed since it was brought to public attention by the Brundtland Report [17] and it has since been developed into a blueprint for reconciling economic and ecological necessities. Daly [18] and Moser [19] (among others Refs. [20–23]) have contributed to make this concept scientifically acceptable so that it is possible to take it as a yard stick for strategic planning. The concept of sustainability can be considered to be the base of strategic planning in two ways: (i) It is an inherent long-term concept. Thus it allows long-term planning in the face of radically changing boundary conditions. (ii) The reference systems are natural flows or states and their variations. Hence, planning on this basis is independent of social conventions like threshold values which may vary with time.

Moser et al. [19] has developed the most operational working hypothesis of sustainability consistent with the needs of ecological process engineering. Based on this definition sustainability requires the following three criteria.

Anthropogenic material flows must not exceed the local assimilation capacity and should be smaller than natural fluctuations in geogenic flows.

This requirement maintains the quality of the material base for ecosystems (soil, aquifers, atmosphere, etc.). It is based on the assumption that geogenic flows are subject to fluctuations, which do not jeopardize evolution and that the local assimilation capacity is a measure of the rate with which ecosystems accept input streams without losing their evolutionary potential. This capacity changes with geography and to some extent with time, too.

Another assumption is that the rate of acceptance of input streams to the supporting ecosystems is clearly more restrictive than any rate of depletion of natural resources. We are facing a 'waste crunch' in contrast to a 'resource crunch', a fact that has been accepted quite widely during the last few years.

Anthropogenic material flows must not alter the quality and the quantity of global material cycles.

Most of the dominant global material cycles (like the carbon, nitrogen or water cycle) have natural buffer stocks. In some cases these stocks are exploitable deposits, in other cases there are unusable storage systems. Today the deposits are mined and exploited very fast, but the knowledge of the environmental impacts of exploitation is insufficient.

This requirement does not totally rule out the use of materials from these natural buffer stocks (like aquifers and fossil raw material deposits) but defines the input streams for industrial systems. It links the rate of exploitation to the rate of replenishment of these natural systems. In some cases even the quality might change, e.g. like for fossil raw materials. Here the main deposition of organic matter occurs by oceanic sedimentation. In this context the most important aspect is to keep the carbon concentration in the global cycles roughly constant. At least at first glance, the form of carbon storage seems to be less important.

The natural variety of species and landscapes must be sustained or improved.

This is a very far-reaching requirement. It calls for maintaining the important interaction between man and nature at a physical as well as a psychological level and for the use of nature's resources under the boundary conditions of aesthetics. Beauty is an intrinsic property of sustainability. Only if we maintain a sufficiently comfortable environment by accepting the rules of natural landscape we can ensure that man will evolve in this system. This can also be seen from a very pragmatic point of view, since land as well as species are factors of the utmost importance in a society pursuing sustainable development. Degrading these factors irreversibly will impede our own chance to improve our quality of life and it will deprive future generations of an important basis for living.

The SPI is based on this definition of sustainability. However, in order to translate the concept of sustainability into a practically applicable measure additional assumptions are necessary.

3. Computation of the SPI

The first consideration concerns the ultimate dimensional unit of a measurement for sustainability. We have chosen the factor 'area' as the basic unit for the computation of the SPI. The reason behind this choice is that in a sustainable economy the only real input that can be utilized in the long term is solar energy. Its utilization per se is bound to the surface area, and area is a limited resource in a sustainable economy since the surface of our planet is finite.

However, area is not only a quantitative measure. In order to generate raw materials in a sustainable way top soil quality has to be preserved to guarantee fertility. The preservation of soil as a production factor requires that material flowing from and to this medium must be limited to sustainable levels. This is also true of material flows from and to the compartments of water and air, which form the other important bases of agriculture. Thus any flow to soil, water or air requires a certain area if it is to be accommodated without endangering long-term fertility.

By taking into account the dual function of area as a recipient of solar energy and as a production factor the SPI can measure and relate the ecological impact of a process with respect to the quantity and the quality of the energy and mass flows it induces.

It is easy to imagine the biosphere as a complex system which optimizes the size of the areas of its subsystems to use a maximum of solar exergy (part of energy that can be utilized). A subsystem can only expand at the expense of others. Thus, land is an increasingly important production factor for ecological process engineering. Processes needing more area for the same product or service are less competitive under sustainable economic conditions.

Furthermore, the SPI can be applied at different levels. Depending on the degree of planning and the location of the process, the SPI can be computed using mean global, national or regional data (see Fig. 2). Once the location is fixed the evaluation can be done in more detail by using regional natural values.

A region is defined as the geographical area which is used to deliver a certain service. However, the size of the region can be different within one process for raw material generation, energy supply and for by-product dissipation or product dissemination. The view from the regional scale needs a very close look at the local (eco)systems, especially at their structures. So the SPI can shift from a strategic measure at an average inter-regional level to a local ecological criterion.

In order to get the SPI, streams (either material or energy) entering or leaving a process are identified by an area. Due to the historic development of process engineering the necessary installations (equipment) for converting raw materials into

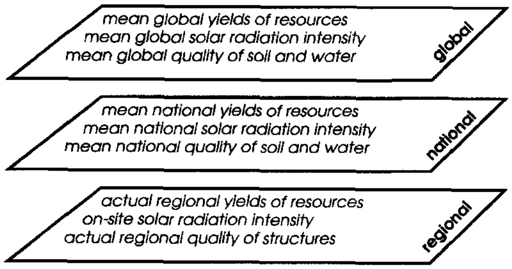

Fig. 2. Levels of application.

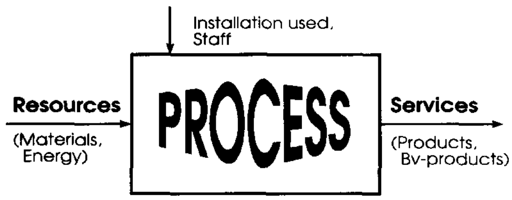

Fig. 3. Basic scheme of a process.

services (products) are calculated separately, even though they consist of matter and energy (Fig. 3).

The calculation of the SPI starts with the computation of the total area A_{tot}, which is assigned in order to embed a process sustainably into the biosphere. This area consists of the area required to produce raw materials A_R, the area necessary to provide process energy A_E, the area to provide the installations for the process A_I, the area required for the staff A_S and the area to accommodate products and by-products A_P.

$$A_{tot} = A_R + A_E + A_I + A_S + A_P \quad (m^2). \tag{1}$$

These areas will be computed on the basis of mass and energy flows and the infrastructural requirements for 1 yr of operation (reference period). Within this year a number of unit-services (product units) S_{tot} (unit/a) will be supplied by the process in question. The area a_{tot} is called the specific sustainable service area or the inverse service yield y_{tot}.

$$a_{tot} = 1/y_{tot} = A_{tot}/S_{tot} \quad (m^2\,a/unit). \tag{2}$$

This specific area is already a possible comparative measure of sustainability if certain services or certain paths to deliver a service are related. In order to make this measure more transparent it is divided by the area per inhabitant in the region relevant to the process. This area a_{in} (m^2 a/cap) is the area available for the yearly supply of goods and energy for each person. It may roughly be estimated by dividing the total area of a region by the number of its inhabitants per year. Analogically, the reference period of a process, the area utilization of one inhabitant, is related to 1 yr. It can be estimated to 24 000 globally or 19 000 (m^2 a/cap) for Europe using population estimates [24] for the year 2000. The SPI is defined as:

$$SPI = a_{tot}/a_{in} \quad \text{(cap/unit).} \tag{3}$$

Physically, it means how much of the area theoretically available for a person to guarantee its subsistence under sustainable conditions is used up to produce one unit-service or product unit in question. The larger the SPI the higher the need for 'area' and the higher the 'sustainable costs' for a given service.

The calculation of the individual contributions to A_{tot} is described in the following section.

3.1. The computation of the partial areas

The raw material area A_R

This area accounts for the sustainable provision of raw materials. Its computation is different for renewable and non-renewable raw materials. The total raw material area is the sum of the areas for renewable and non-renewable materials consumed by a process.

The renewable raw material area A_{RR} (including the fossil organic raw material area A_{RF})

Renewable raw materials take part in at least one global cycle. For this category of materials the area required for production is the area needed to convert the building blocks available in the biosphere into biomass which is subsequently fed into the process. Thus the specific yield y_R (kg/m^2 a) and the feed F_R (kg/a) of a processed resource are the basis of computation:

$$A_{RR} = F_R/y_R \quad (m^2) \tag{4}$$

Table 1 lists some average yields of renewable resources in Central Europe. It is very important to note that in this case the area also accounts for the ultimate disposal of the product since it embeds the raw material generation into global material cycles. From this point of view the same treatment can be applied to fossil organic raw materials. So they can be treated as renewable resources albeit with a low rate of regeneration. The reason for this is that at any given time there is a stream from the global carbon cycle into a long-term storage compartment. This is mainly realized by sedimentation into the beds of the oceans. When fossil raw materials are used at the same rate at which carbon is removed into long-term storage, there is no alteration of the global cycle itself and no unsustainable accumulation occurs (e.g. in the atmosphere). However, the area to 'produce' 1 kg of organic sediment per year is about 500 m^2 [25, 26], which means a yield of 0.002 kg/m^2 a.

The non-renewable raw material area A_{RN}

Non-renewable raw materials cannot be embedded into global material cycles. Their use is inherently dissipative, which has to be taken into account when

Table 1
Fresh harvest yields of different renewable raw materials in Central Europe

Raw Material	($kg/m^2 a$)
Winter wheat	0.515
Summer wheat	0.414
Rye	0.412
Winter dredge grain	0.416
Summer dredge grain	0.389
Barley	0.481
Oats	0.369
Corn	0.848
Rapeseed	0.284
Potatoes	2.364
Sugar beets	4.903
Mangel-wurzel	4.570
Green and silo corn	3.985

computing the area necessary to accommodate products and by-products into the biosphere. However, their generation needs energy and other expenditures.

In order to get a rough estimate for the A_{RN} of substances only the energy demand is considered. Usually the precise energy content per mass unit is not available. In these cases the following procedure is proposed, where the price of the raw material (which is well-known) is the base of computation:

$$E_D = C_N \cdot 0.95 / C_E \quad (kW\,h/kg) \tag{5}$$

In this formula E_D is the energy demand to supply 1 kg of the material in question, C_N is the price of this material (world market price, taxes excluded) and C_E is the price of 1 kW h of energy (industrial price, taxes excluded). This relation is based on the assumption that energy almost exclusively defines the prices of basic raw materials. Although this seems to be a very crude estimate it is true for a large number of staple products with only minor deviations from the factor 0.95.

In order to obtain an area for the generation of non-renewable raw materials it is necessary to calculate an area per energy unit. As the conversion and upgrading of primary raw materials (like ores) is almost exclusively performed on industrial scale, this calls for the definition of a mean industrial energy supply density (or mean industrial energy yield) y_{EI} ($kW\,h/m^2\,a$) under sustainable conditions. This yield takes into account the energy mix (process heat, electricity, mechanical power, etc.) used in a sustainable industry:

$$A_{RN} = E_D \cdot F_R / y_{EI} \quad (m^2) \tag{6}$$

The y_{EI} may vary with the geographic context and with the technologies used in the technology mix to supply the energy. However, as a result of numerous case studies carried out by the authors in this field, it may be stated that this variation is confined to a relatively small range between 2 and 12 $kW\,h/m^2\,a$.

The energy supply area A_E

The area needed to supply 1 kW h of service energy under sustainable conditions varies considerably with the quality of the energy needed (different temperature levels of process heat, electricity or mechanical power, liquefied fuel, etc., see Table 2). As a rough guideline we can say that the higher the quality of the energy service the higher the area required for supplying it. Besides, storage of energy (e.g. in liquid fuels) is costly in terms of sustainable area requirement.

The energy yields in Table 2 also include the infrastructural needs for the generation of energy (see below). There are large differences in the ratio between the area needed to provide the energy (which is a function of the effectiveness of the transformation of solar energy into the energy form needed) and the area needed to establish the infrastructure for this transformation (which depends on the complexity of the technology and on the necessary technical effort).

The energy supply area is calculated using the energy yields for different energy qualities y_E (kW h/m^2 a) and the energy F_E (kW h/a) utilized in the process:

$$A_E = F_E/y_E \quad (m^2). \tag{7}$$

The area for process installation A_I

The area needed to provide the installation for a process is divided into two segments: the 'direct' use of land (i.e. the land occupied by the process installation itself) and the 'indirect' use of land (i.e. the area to provide and maintain the installation in a sustainable way). These two segments have to be treated differently:

$$A_I = A_{ID} + A_{II} \quad (m^2). \tag{8}$$

The direct use of land A_{ID}

Land used directly is an area which is occupied while the process is operating. So it has to be included into the total area in the same way as the raw material area or the energy supply area.

Indirect use of land A_{II}

The area to establish the infrastructure for a process is needed only once in the lifespan of a plant. In order to be comparable to the other areas, which are based on

Table 2
Service energy yields from one square meter of some energy conversion technologies in Central Europe: all values in kW h/m^2 a

Type	Heat	Electricity	Mobility
Solar-collectors	100	—	—
Photovoltaics	10	12	7.5
Waterpower-station	35	43	26
Energy from woody plants	3.7	1.6	1.2
Ethanol from sugar beets	1.8	0.8	0.5

the consumption per year, this area has to be 'depreciated' like an investment over the lifespan of a plant.

Most installations are made of non-renewable raw materials. However, unlike raw materials used in a process most of the materials forming the process infrastructure can be reclaimed after their use in the process and can be recycled. So their use is not dissipative. The ecological impact is merely caused by the creation of the installation.

Similar to the assumption and the evaluation of the area for non-renewable raw materials the energy demand for this procedure will be estimated and converted into an area required. Subsequently, the resulting 'depreciated area' (over the lifespan LS (a)) will be included in the A_{II}. This energy demand can roughly be estimated from the total costs C_I (\$) (industrial price, taxes excluded) follows:

$$E_D = C_I \cdot 0.54/(C_E \cdot \mathrm{LS}) \quad (\mathrm{kW\,h/a}) \tag{9}$$

$$A_{II} = E_D/y_{EI} \quad (\mathrm{m}^2) \tag{10}$$

or by using an area revenue y_I:

$$y_I = C_E \cdot y_{EI} \quad (\$/\mathrm{m}^2\,\mathrm{a}) \tag{11}$$

$$A_{II} = C_I \cdot 0.54/(y_I \cdot \mathrm{LS}) \quad (\mathrm{m}^2) \tag{12}$$

or by combining a lifespan of 15 (a), an industrial energy supply density of 6 kW h/m^2 a and energy cost of 0.02 \$/kW h to one factor:

$$A_{II} = 0.30 \cdot C_I \quad (\mathrm{m}^2). \tag{13}$$

As a matter of fact areas representing the installation of processes do not usually dominate the SPI. Notable exceptions are energy conversion technologies and agriculture, where direct use of land is important.

The staff area A_S

The number of workers N_S (cap/a) in a factory is allocated to an area. The more staff a process requires the bigger the impact on the environment. Consequently, personnel needed for farming, distribution and running the plants must also be included in the calculation:

$$A_S = N_S \cdot a_{in} \quad (\mathrm{m}^2). \tag{14}$$

To keep consistent with the factor yield, let y_S (cap/m^2 a) be the inverse area a_{in}. This may help us to recognize that we are as dependent on areas physically (and therefore also psychologically) as any other creature:

$$A_S = N_S/y_S \quad (\mathrm{m}^2). \tag{15}$$

This area allows us to relate labour and matter and/or energy intensive processes to one another. Nowadays about 100 000 dollars are invested to get one person unemployed. If we use this value in Eq. (13), we end up at 30 000 (m^2) which would be rather costly under sustainable conditions.

The area for sustainable dissipation of products A_P

Any stream leaving a process is considered to be a product stream, regardless of whether it can be sold or whether it is economically worthless. It is furthermore supposed that all products including the by-products are eventually dispersed into the environment. So their quantity and quality have to be considered.

For a number of elements, namely carbon, oxygen, nitrogen and hydrogen global cycles exist. The other elements of which a living cell is composed (phosphorus, potassium, sodium, chlorine, sulphur, cobalt, copper, magnesium, etc.) are recycled on a more regional scale. A process within a sustainable economy will be embedded into these cycles and support the natural chronology, e.g. recycling ash from biomass combustion or cells from fermentation. The area for raw material generation takes into account the creation of raw material from the building blocks of these cycles.

However, the case is different with non-renewable materials, which are those that basically do not form global cycles like metals and halogens. Their use is inherently dissipative and the area to be taken into account in the SPI is the area which can accommodate the product flows.

The basic idea behind the calculation of this area is that dissipation must be related to natural rates of regeneration and natural qualities. For the two environmental compartments 'soil' and 'water' such rates and qualities can be defined in a way that sustainable dissipation is guaranteed. Streams to the compartment 'air' are treated as if they were completely dissipated into either 'soil' or 'water' (see below).

In order to estimate the area allocated to dissipation, the following reasoning is applied. If there is a rate at which the content of a given environmental compartment is renewed, any product stream can be 'diluted' by the newly added mass, until this mass reaches qualities (concentrations) that are equal to the quality of the initial compartment.

Therefore, it is necessary to know the rate of renewal of a certain environmental compartment and the actual concentration of different components (e.g. heavy metals, sulphur, chloride, etc.) in this compartment. So the product area can be calculated using the rate of renewal R_c (kg/m^2 a) of the environmental compartment, the actual concentration of the substance c_i (kg$_i$/kg) in the compartment and the product flow $F_{P,i}$ (kg$_i$/a) to this compartment (index i describes a certain substance).

In contrast to the definition of yields, dissipation is linked to sinks ('sinks' in contrast to 'sources'). These sinks s_P are described by the rate of renewal and the actual concentration:

$$s_{P,i} = (R_c \cdot c_i) \quad (\text{kg}_i/\text{m}^2\,\text{a}), \tag{16}$$

$$A_{P,i} = F_{P,i}/s_{P,i} \quad (\text{m}^2). \tag{17}$$

This calculation must be made for all product flows leaving the process in question. The area $A_{P,s}$ assigned to the dissipation of a certain product stream 's' is the largest area $A_{P,i}$ computed for this stream (either in the compartment water or soil). The product dissipation area A_P is calculated as the sum of the individual dissipation areas:

$$A_P = \sum A_{P,s} \quad (\text{m}^2). \tag{18}$$

We will now discuss the way to obtain the dissipation areas for different environmental compartments.

Dissipation into the compartment 'soil'

There is a process that creates a material similar to top soil. This is the process of composting. In order to obtain a certain amount of compost and to renew soil, biomass is needed. Biomass, in turn, needs area to grow. Thus, there is a rate to create compost that is related to area. This rate can be estimated to be 0.42 kg/m^2 a. This is a typical value for Central Europe, where there is a loss in mass during composting of 56% (values for grassland in Austria).

Concentrations of a great number of components in top soil are known. These concentrations certainly vary with the geographic location. Table 3 lists allowable dissipation rates for some heavy metals and organic substances based on actual concentrations in top soil (average values for Austria).

Dissipation into the compartment 'water'

In this case the rate of replenishing is governed by the annual rate of precipitation, which is also well-known. However, we have to take into account that only a part of the water precipitated will actually be buffered in soil or reach the ground water. The percentage of evaporation differs with the climate. It is about 70% for Central Europe.

With the annual precipitation rate of 1200 kg/m^2 a we get a rate of replenishing the compartment 'water' of 360 kg/m^2 a (Central European values). The quality (concentration) of ground water is the measure used in Eq. (16) to estimate the dissipation of components into the compartment 'water'. Table 4 lists values for some important substances.

Dissipation into the compartment 'air'

The compartment 'air' is very dynamic. Local concentrations vary very quickly in time and space. It is not possible to define rationally a rate of renewal for this

Table 3
Allowable yearly dissipation into the compartment 'soil' with a compost generation rate of 0.42 kg/m^2 a

Heavy metal	(mg/m^2 a)	Heavy metal	(mg/m^2 a)	Organic substance	(mg/m^2 a)
As	8.4	Ni	25.2	PAC	0.13
B	10.5	Pb	42	PCDD	2.1×10^{-6}
Be	4.2	Sb	2.1	PCDF	2.1×10^{-6}
Cd	0.42	Se	2.1	PCB	0.042
Co	21	Sn	8.4		
Cu	42	Th	6.3		
Hg	0.42	Tl	0.42		
Li	25.2	U	2.1		
Pb	42	V	21		
Mn	840	Zn	126		
Mo	2.1	Zr	126		

Table 4
Allowable yearly dissipation into the compartment 'water' with a precipitation of 1200 kg/m^2a and a seeping ratio of 30%

Heavy metal	($mg/m^2 a$)	Heavy metal	($mg/m^2 a$)	Organic substance	($mg/m^2 a$)
As	14.4	Mn	18	HC total	36
B	180	Ni	10.8	PAC	0.072
Be	1.8	Pb	14.4	AOX	10.8
Cd	1.8	Sb	3.6	BTX	10.8
Co	18	Se	3.6	PCB	0.036
Cu	36	Sn	18	COD	7200
Fe	36	Tl	0.22	DDT. TDE	0.036
Hg	0.36	V	18	lindane	1.08
K	3600	Zn	1800	vinyl chloride	0.11

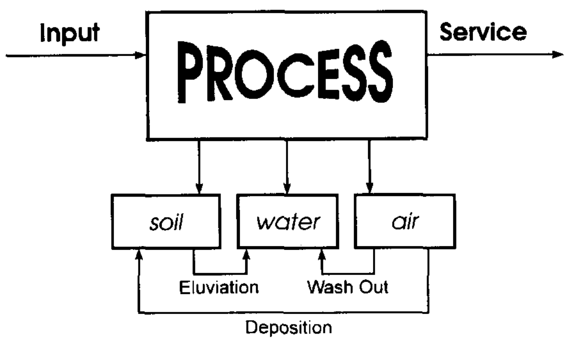

Fig. 4. Classification of dissipated streams.

compartment. However, most streams to this compartment will eventually end up in the compartments 'soil' and/or 'water' (see Fig. 4). Therefore, it seems sensible to treat streams to this compartment as if they were dissipated into soil and/or water.

Although this simplification excludes some important problems of atmospheric chemistry, it will lead to a pragmatic approach. Besides, the compartment 'air' seems to be already protected by stringent emission laws (emission limitations on SO_x, NO_x, VOC, HCFC, etc.) which in any case have to be observed when implementing a certain technology.

For evaluating the product dissipation area the following scheme is used.

– Every emission of building blocks of global cycles may be omitted from considerations since no further degradation is needed.

– If only a comparison between processes generating the same service (product) is needed the product itself can be neglected.

– For every substance stream the respective areas for sustainable dissipation into the compartments 'soil' and/or 'water' are calculated. As a general rule, the larger area (dissipation into either water only or soil only) will be defined as the basis for calculation. If more detailed knowledge exists the actual substance flow to each compartment has to be taken into account. Then, the overall area is the sum of both areas.

4. Conclusions

The SPI offers a chance to include ecological considerations into strategic planing of process technologies. It is a measure that may readily be computed with basic engineering data like mass and energy balances, prices of staple raw materials and installations. These data are usually available even at an early stage of planning. In addition to these data, knowledge is required of natural qualities of soil and water as well as on yields of renewable raw materials. The data base of the SPI is invariant with time contrary to limit threshold values or risk assessment for chemical substances.

The basic assumption of the SPI is that of embedding a sustainable process into the environment. It avoids a substance to substance assessment of ecological impact which is not operational for strategic planning given the spotty and inconclusive knowledge on ecotoxicity today.

As an easily computed measure with a clear and understandable base and meaning, it allows a rational discussion of different technological alternatives in process industry. The SPI may be applied to technology assessment problems as well as process optimization. Given the sound long-term perspective of the concept of sustainability it is a valuable additional tool to arrive at decisions which can sustain future ecological assessment and which will prove competitive in a future economic setting.

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