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A COMMON FRAMEWORK FOR EMERGY AND EXERGY BASED LCA IN ACCORDANCE WITH ENVIRON THEORY

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ABSTRACT

To estimate the environmental consequences of human activities with the purpose of achieving sustainable development, we need to carry out detailed analyses of the material and energy cycles of our society. The need to choose from several options is not a simple task. There are several reasons to this. First, the task contains an inherent problem of finding a common unit. Second, we need a common and unified methodology for matter and energy to compare results and evaluate systems using various types of analysis like life cycle assessment and material flux analysis. It is widely recognised that energy analysis following the first law does not bring us much further in this context as it hardly gives any reliable indications on where to take action. Two recent measures, exergy and emergy, seem to offer the possibility of facilitating the process, by making it possible to find a common unit to both matter and energy and in addition bring in the perspectives of total environmental costs (a sort of 'ecological footprint' – not in the strict sense) to the evaluation. The concepts may be used separately, but recent results from natural ecosystems indicate that the use of the two in combination might bring us even further in defining and achieving sustainable development. This in turn also allows us to construct new indicators specifically dedicated to and addressing the sustainability trends in the production systems or even society and may eventually be coupled to economics, at least at a micro-economic scale. The approach presented makes it possible to analyse the sustainability state of the systems in general software packages able to do a simple linear optimisation, and thus brings in the possibility of finding the most optimal way of coupling material and energetic fluxes and thus assist in implementation of cleaner production and industrial ecology. To our knowledge, this is the first time a common, unified approach to the analysis of both cultural and natural ecosystems is presented.
Keywords: emergy, environ, exergy, LCA.

1 INTRODUCTION

Life cycle assessments (LCAs) and material flux analysis (MFA) are only a few of the many methods proposed in literature [1], which together with economic evaluations like environmental audits make an important platform of necessary tools that help us to improve our understanding of production processes and achieve cleaner production.

Carrying out an LCA or MFA, although detailed through the work put forward in the guidelines by ISO and OECD, is not an easy task. Taking a look at the various studies that have been undertaken during the latest decades, the picture that comes out does not give the impression that equivalent and compatible strategies have been followed. Often the studies will include details particular to the item and production cycle under study. The production may be dominated by problems stemming from either resource extraction, waste management problems, or problems related to energy or material flows [2]. While such attempts are needed and sympathetic, their exact value is doubtful if their value 'currencies' are too different.

LCA and similar assessments are often carried out on the basis of either material or energy flows of the industrial production system or unit under focus, rarely both [2]. The reason is clear. Building the analysis on the flow of material fluxes (MFA) often tends to focus on single or only few substances under consideration, chosen to be of interest from either a quantitative and/or qualitative perspective. The energy alternative(s) to analysing material flow would be to carry out analysis of energy flows based on energy conservation, the so-called first law analysis or better to carry out an

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analysis that includes irreversible, dissipative losses due to one way conversion of energy of higher to lower quality with the resulting formation of entropy, the so-called second law analysis [3, 4]. Thus, a tight coupling possibility lies in the use of thermodynamic approaches as demonstrated for instance by Bakshi [5].

Many indicators of societal development have been developed since the Rio Conference in 1992. The indicators presented as an outcome of this conference (United Nations Division for Sustainable Development 1992 are aimed at describing what a sustainable society is about and how to achieve it. For these concepts not to remain oxymorons, more elaborate definitions and guidelines than hitherto are needed. One aspect though, is that clearer definitions should help us to achieve the goals of sustainability [6, 7]. The other aspect of getting there, to an actual sustainable society, is how we practise and implement things, i.e. how we convert our knowledge into an actual achievement of the desired goal, merely seems to be a question of action. But action, and even to take the right actions, at any level, requires that we have good indicators that are able to point out the right direction, the road to get there! This may sound somewhat trivial but many obstacles, among others political and socio-economical, exist on the path to sustainability.

In addition, approaches like LCA and MFA suffer from the fact that it is not always possible to compare the results of the various types of analysis, due to the dualism between matter and energy. The lack of a common 'currency' makes a common unified evaluation impossible, similar to the traditional problem of comparing apples, pears and bananas. Thus there is a need to find a way to combine energy and matter and bring them on a common platform. One way out may be to find a common currency to the two. A similar problem is found when coupling various types of analyses to economy. This does not only imply that everything may be converted into money but, in fact, also that we perfectly know how to do it the right way, i.e. that the monetary evaluation is correct.

Meanwhile, economic evaluations and environmental auditing seem to have their own well-known problems too [8]. Economy may be important for a production system of a factory to survive, but an economical input–output analysis alone does not reveal where really to put an environmental effort, for instance, to achieve cleaner production [9, 10]. Only detailed knowledge of fluxes together with potential technical improvements and knowledge about all options does this.

Two relatively new concepts, exergy [11–14] and emergy [15–19], seem to offer a possibility of linking analysis of material and energetic flows by defining a common currency for the two approaches. One is basically a second law analysis built on the traditional concept of exergy [20] and the other, emergy, is built on an idea and the work of H.T. Odum [16]. The common currency or unit value of both concepts, exergy and emergy, is energy (joule, calories) or solar equivalent joules, respectively.

Both exergy (by definition the maximum amount of work that may be extracted from a given amount of energy) and emergy (embodied – or better 'memorized' – solar energy) are concepts that have been used, for many decades, to tell us 'something' about environmental systems. This goes from the understanding of material and energy fluxes in ecosystems, mainly aquatic systems, to the understanding of production activities, and even establishment of environmental balances of regional activities [21] or whole countries [22, 23].

Exergy in its classical sense has a strong foundation in thermodynamics, especially the second law. The concept is maybe not as well known as it ought to be (eventually recognised as late as 1987), but is currently being used in many domains like chemical process engineering, hydraulics, and so on with the purpose of optimising the energy efficiency of such systems. Thus, clearly connecting to economy studies using this concept on production system also correlates to the works of the economist [24].

Emergy, as recently demonstrated [25], can be derived as a function of exergy, but carries a totally different meaning and rationale: not all energy and exergy are equal; if the amount of direct and indirect solar energy required to produce a certain item is high (after a process of selection), it means that the item is valuable for the system, regardless of the exergy it potentially carries.

Exergy and emergy share an important feature in that they are both able to embrace vaguely defined concepts like 'ecological backpacks' and 'ecological footprints' and bring them into the realm of possible quantitative analysis, finally as one aggregate unit [5]. One advantage of aggregation is that it will allow making an overall comparison of performance between systems. The obvious disadvantage is that aggregation inherently has the consequence of hiding details and thereby not revealing where action should be undertaken if system performance is found to be sub-optimal. The challenge will be to set forward a strategy that allows us to do both.

Understanding production systems and their related activities as environs – and at the same time ensure a coupling to the concepts of exergy and emergy may be a solution to the dilemma described above.

The environ concept, normally used to describe ecosystems by Patten and co-workers [26], understanding allows us to describe the system in a consistent manner, in terms of quantity and quality of fluxes. The coupling to exergy ensures a common unit (joule or calories) for both energy and material fluxes, and tracks valuable dissipative fluxes of high-quality energy which should be avoided. Emergy calculations provide a cumulation of the costs of the production on the input side and allow us to account for the load of all incoming fluxes.

Whereas both emergy and exergy analysis have been carried out in many cases for both single processes and regional analysis of material and energy flows, so far no clear strategy for setting up these types of analyses separately or in combination has been proposed.

This article aims at developing a framework for this purpose. The strategy will build on an understanding of the production system as an environ [26] allowing to couple individual production units to each other at higher hierarchical levels, like in industrial ecology systems or even at community and society level. On one hand, the approach allows a full aggregation of knowledge into so-called 'holistic' indicators without losing the possibilities to track the exact causes at a later point in time.

2 THE CONCEPTS TO BE COMBINED

To summarize, the approach to the analysis of systems subjected to environmental management proposed here is a merger of three concepts:

1. emergy, which represents the energy costs of a product or activity, when taking it back to its origins in solar power;
2. exergy, which allows us to make a distinction between different quality of energies, i.e. how available or useful they are, and thus suggests where it is sensible to take action when optimising systems;
3. the environ concept [26], which not only represents a way of thinking that improves the possibility of understanding how the system works, but also includes a methodological structure to the thinking as it allows a rigid transfer of problems of environmental management into a mathematical formalisation and conceptualisation of particular systems elements into matrices notation.

The three concepts will be discussed briefly here with a relatively simple introduction to the fundamental ideas behind the concepts. This should allow for an intuitive understanding of the idea of the article. Readers interested in more details, to get a full presentation or to get an introduction into the original application of the concepts will have to refer to a variety of books or specific articles. The concept of the ecosystem as environ and network treatments hereof is thoroughly treated in

Higashi and Burns [27]. A synopsis of emergy and applications are presented in several books by its originator H.T. Odum [15, 19]. Exergy, despite having its origins in the early part of the last century, first seemed to have a breakthrough at the international level around the 1990s, when it was introduced in several college textbooks [28, 29]. For recent treatments of the extended application to far from equilibrium systems at high levels of hierarchy see [30].

3 THE ENVIRON CONCEPT

As a result of the conceptualised treatment of systems as environs, a more formalised presentation of the concept and its transfer into a mathematical treatment is necessary. The concept of environ by B.C. Patten [26] is a transfer of the ideas of the Estonian physiologist and ethologist Jacob von Uexküll to the ecosystem level. Being a very foresighted scientist in his area, von Uexküll [31] was one of the first to present a model on how animals receive and perceive stimuli, react and act to (changes in) their environment.

According to Patten, ecosystems and their constituting parts, i.e. functional or trophic components, may be viewed as entities with the same relationships to the outside world as von Uexkülls animals. He refers to those entities to as environs [26]. The system together with its components are designated as X and X_i, respectively; they receive inputs and are influenced from either the outside world or other components within the system. The whole is referred to as the input environ, and the external part of the input environ is designated as Z. The internal relations usually consist of either material or energetic fluxes, f_{ij}s between components. In turn matter and energy may be passed on to other components in the ecosystem network or to the outside world. This whole is the output environ of which the fluxes to the exterior is designated by the vector Y (Fig. 1).

In general, networks, and thus also ecosystem networks, may be described by various isomorphic types of presentations, either as directed graphs (digraph), nodes connected with edges or arcs, box diagrams with arrows or simply a directed matrix. Retaining the usual convention of matrices, with the letter i designating rows and the letter j designating columns, a matrix containing all the flow elements, f_{ij}s, of the systems may be constructed. In the case of the environ approach of Patten,

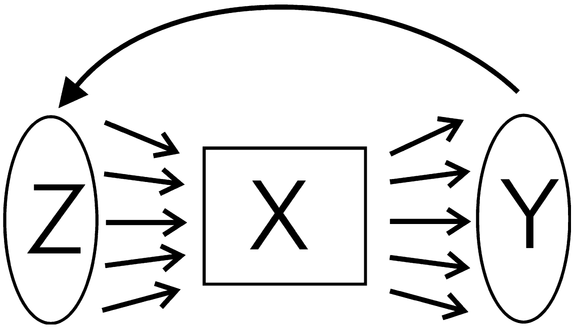

Figure 1: A visualisation of the environ concept introduced by Patten after von Uexküll. The environ, X, consisting of several elements $X_1, \ldots, X_n$, receives impulses from the outside world (environment) through the vector Z, and passes impulses on to the outside world through the vector Y. Through the feedback, usually referred to as a function cycle, it has the possibility of influencing itself indirectly.

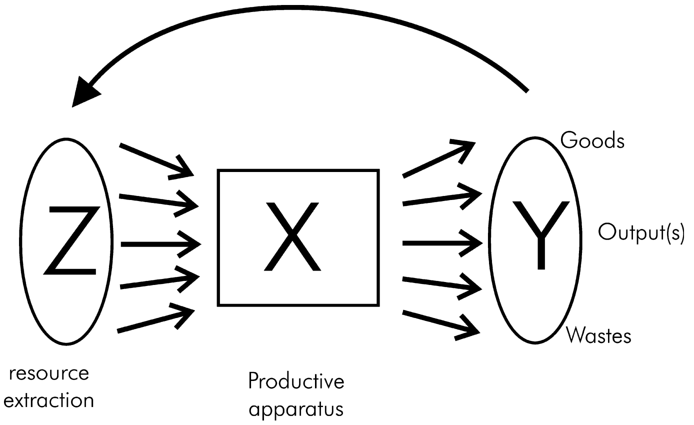

Figure 2: The figure shows how a production of a certain good (or service) may be interpreted within the environ concept. The input environ corresponds to the resources needed for the production. Within the environ itself, energy and matter are allocated. The output environ comprises the goods produced together with wastes and dissipations.

a direction from columns to rows has been used, i.e. the element $f_{i,j}$ is read as the flow to j from i. Balances of either mass or energy (according to the first Law) may be established through eqn (1)

$$\frac{\mathrm{d}X_i}{\mathrm{d}t} = \sum f_{i,z} + \sum_j f_{i,j} - \sum_i f_{i,j} - \sum f_{y,i}, \tag{1}$$

for each of the environ's constitution parts, each of which will be equal to zero under the assumption of steady state or dynamic equilibrium. This is the basic part which gives us a consistent methodology to track flows of a system and as we shall see later also allows us to readily establish various efficiency indices.

According to the environ view of the world, we may now visualise a simplified human production system as presented in Fig. 2.

The resource extraction(s) undertaken to produce any product or service or the necessary production facilities itself makes up the input environ of the productive apparatus 'sensu lato'. Within the production apparatus, the environ, material and energy fluxes are exchanged according to the various processes needed to produce the good or service. Eventually, the output environ of the production is made up of goods and services as well as wastes produced during the process. The function cycle will represent various reuse and recycling activities, waste storage as well as pollutants. The importance of this feedback cycle varies in accordance with the level of implementation of strategies which considers cleaner production and industrial ecology activities.

4 THE EMERGY CONCEPT

While the concept of emergy may be difficult to practise in real life, the idea is easy to capture and therefore appealing. First, all energy reaching the earth comes from the sun [15, 32, 33]. The energy, or more precisely a part hereof, is captured on a short term by primary producers in their biomass.

During certain periods in the evolution of our planet, substantial amounts of biomass were buried or enclosed and converted by pressure and physico-chemical reactions into what we now know as fossil fuels. Materials, in the form of elements, are believed to be distributed throughout our universe in a homogenous manner. On a particular planet, the overall distribution is thus the same everywhere, but the specific history and evolution of a planet will allow for local concentration of elements, e.g. in ores. To concentrate elements, making them sufficiently pure to be used in products, we need to apply technologies to change them. These technologies predominantly use fossil fuels as the energy source. The consequence is that the emergence of any product can be taken back to its original costs in terms of the solar radiation entering the earth and eventually needed to construct them. This part will be considered the input environ of the product. The (solar) energy costs will accumulate over all steps taken in this input part of the life cycle, e.g. the extraction process, purification, production of elements by subcontractors, assembly by final producers, need for machinery and workers, and in addition transports between the mentioned links. All the mentioned energies are needed before a product, good or service can appear/emerge.

Emergy represents a way to express this cumulative energy cost of a product. The total costs are considered to be embodied in the product, therefore the term emergy. In other words, the mere energy content of a product, which may easily be measured by, for instance, calorimetry, does not reflect the above-mentioned costs at all. Therefore, we need to multiply by a factor usually referred to as the transformity, τ. As the actual costs of various processes and products have become established over the years, the emergy content has become easier to calculate for more and more products. A simple illustration based on a hypothetical ecosystem, a simple food chain, is presented in Fig. 3.

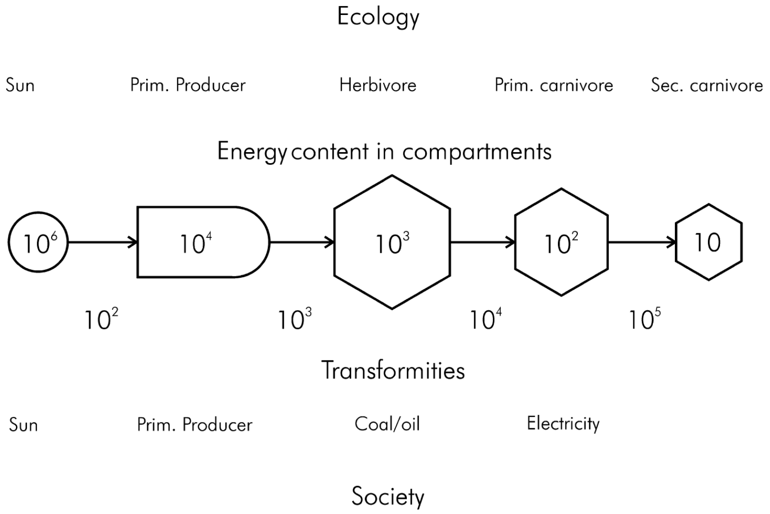

Figure 3: A simple linearly organised system which may be understood as an ecosystem food chain or a simple energy production system. The energy, captured from the sun with a photosynthetic efficiency of 1%, is transferred through the ecosystem food chain with the Lindeman efficiency of 10% leading to the given biomasses. From this the corresponding transformities may be constructed as all components originate from the equivalent amount of solar radiation. The same approach can be taken for production and societal systems as indicated in the lower part of the figure.

Calculations are not always as simple as the above-mentioned scheme would indicate. Transformities for goods that seem alike from a functional perspective may vary a lot. As an example, consider two chairs, one made of wood and the other with a plastic seat and metal frame. Whereas the first may be constructed from a material with a low transformity and manpower alone, the second will, for instance, require crude oil for plastic, an energy source for extraction of metal from ores and melting during the construction process and design before the final product can be reached. Another problem receiving specific attention has been the problem of cogeneration [34], where by-products are used as resources.

The advantage is that emergy comes out with the same dimensions as energy as it just reflects accumulated energy values behind a given product or service. Meanwhile, to distinguish between the simple energy content and the emergy value of a product, the unit of SeJ has been introduced (SeJ stands for solar equivalent joules or solar em-joules).

As mentioned before, emergy is not always a simple approach to apply. The rigid and consistent structuring of flows, as they appear after they have been organised according to environ theory, is believed to assist in overcoming many problems known to exist.

5 THE EXERGY CONCEPT

The basic definition found in most textbooks is that exergy is the maximum work that one can get out of a system or process with reference to its environment. Hereby, a quality perspective is added to energy, since various forms of energy may be equal in quantity, but at the same time may differ a lot in their ability to do work. In other words, different energy forms also differ in the amount of energy that is available to do work. The energy in materials, like in isotopes, may be compared with the same amount of energy in the form of heat. Meanwhile, we may get work (to be used for other purposes) out of the first system, whereas our chances of getting something 'sensible' out of the latter are small.

The understanding of varying energy qualities needs to be coupled to irreversibility, i.e. the fact that all energy transformation in the real world is happening in one direction only. Energy is only transformed from high quality to a low quality form, from high to low(er) exergy or availability [35]. The part of exergy changed during transformation, i.e. representing the lowering in value, is the part of the energy ending up as entropy and not any longer available. With high-quality energy forms such as radiation and electromagnetic waves, we may talk about a low entropy form of energy, while heat with the lowest value is referred to as a high entropy form.

It is now clear that keeping track of the exergy content or flows of in a system offers several advantages to simple energy balances [36–42]. The simple energy balance, or first law analysis as it is often called, is a simple book keeping system. But it does not reveal anything about the qualities of energies, i.e. whether the energies are available or not. Thus, it does not convey where any amount of energy of high values is lost and where it would be sensible to put efforts to optimise the system. Therefore, accounting of energetic fluxes should be kept on the basis of exergy rather than energy.

Keeping track of flows in terms of exergy includes another advantage in addition to keeping track of real energy values and evaluation of necessary and unnecessary dissipations. Since both energy and material fluxes may be calculated and evaluated on the basis of exergy, we now have a common currency that allows us to compare the two types of fluxes.

6 INDUSTRIAL (ECO)SYSTEMS AS ENVIRONS

One major question can immediately be raised. How to overlook systems at high level of complexity like ecosystems, production systems or societies, say even to optimise their function with respect to

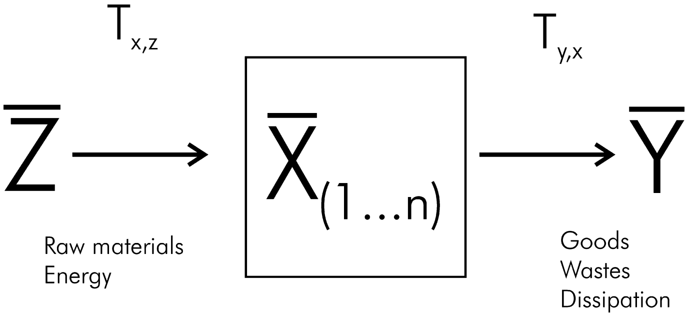

Figure 4: A simple matrix representation of a production system corresponding to the system presented in Fig. 2. The environ is a matrix representing the processes and flows involved in the production process. The output and input environs are represented as vectors (if the original notation of Patten is used as row and columns, respectively).

material and energetic fluxes and cycles. This is where the merger between the presented approaches opens up a possibility. The basic representation of the production process in matrix and vector terms isomorphic with Fig. 3 may be depicted as in Fig. 4.

All the above-mentioned ideas have been applied to ecosystems throughout the recent centuries and at least some knowledge has been created. Meanwhile, applications have been made using one method or the index only.

Aggregating the indices, like emergy and exergy [5, 43], one may gain important insight to the systems, but one will also loose, of course, the possibility to say exactly how things come by or how development of the system takes place. Also it is commonly recognised that using a single aggregated index, although sometimes enough for a quick comparison of systems at particular snapshots in time, is rarely enough to give the whole picture of the system.

Emergy and exergy, chosen from the many proposed orientors of ecosystems, do seem to go very well together. Emergy conveys something about the costs and exergy indicates how well it is 'organised'. Thus the exergy/emergy ratio may say something about how much structure one obtains per previously accumulated solar energy unit and thus can be an expression of the overall efficiency of the system. The efficiency can actually be seen in different ways, according to the time span and to the aspect of sustainability we want to observe [44].

As pointed out above, to work at a very aggregated level may serve only to hide the not so obvious relationships in a complex system. So to work with emergy and exergy on the level of production and societal systems, probably one will be forced to go into more details [45, 46]. But if this has to go in the direction of opening up possibilities to achieve a (more) sustainable system, the increase in details will have to take place in a certain strategic direction.

First, a distinction between material and energetic, or rather exergetic, fluxes has to be made. This is presented in an environ-like manner in Fig. 5.

Thus the exergy flux, f_{iz}, related to the input environ in terms of exergy may be split into parts belonging to the supply of materials or energy (see eqn (2)):

$$f_{iz}^{\text{total}} = f_{iz}^{\text{mat}} + f_{iz}^{\text{en}}, \tag{2}$$

where f_{iz}^{mat} and f_{iz}^{en} are the material and energy part, respectively (Fig. 5). The exergetic outputs may be stated in an equivalent manner, but now another split may be made (see eqn (3)):

$$f_{yi}^{\mathrm{total}} = f_{yi}^{\mathrm{mater}} + f_{yi}^{\mathrm{en}} = f_{yi}^{\mathrm{goods}} + f_{yi}^{\mathrm{waste}} + f_{yi}^{\mathrm{en,diss}} - f_{yi}^{\mathrm{en,non\text{-}diss}}. \tag{3}$$

This has to do with the dissipation problem. When the exergy leaves, will the system still have some work potential in it? Is it still available to processes in the system, for instance through cleaner production initiatives, or to processes in other systems to which it could be coupled through initiatives like industrial ecology? Or is it totally dissipated? For a matrix representation of the problem see Fig. 6.

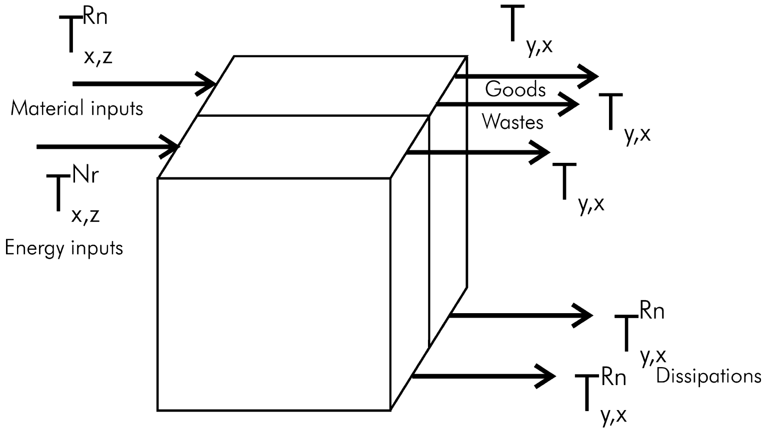

Figure 5: The environ shown formulated in terms of two types of exergy (or emergy) necessary to drive the system. The energetic part (front) stems from input exergies from all sorts of energy production, whereas the material (back) part is derived from the input of extracted raw materials.

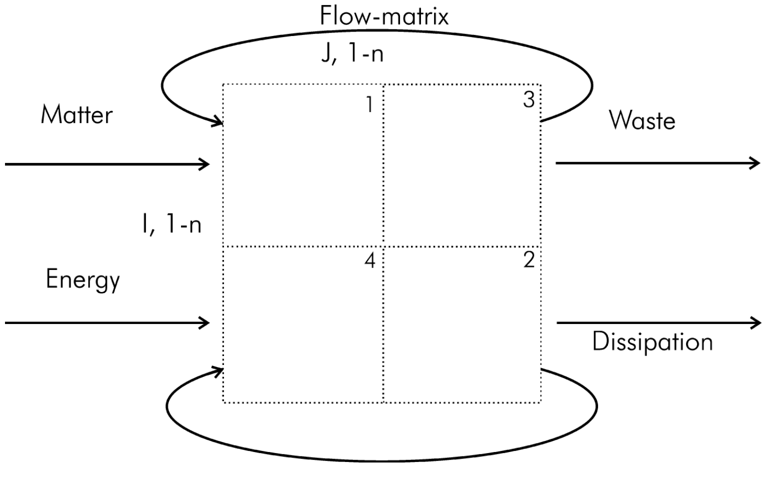

Figure 6: A matrix representation of the production system depicted in Fig. 5. The left part now contains the material flows and the right energetic flows (quadrant 4 will generally be void as matter does not become energy under normal conditions of production).

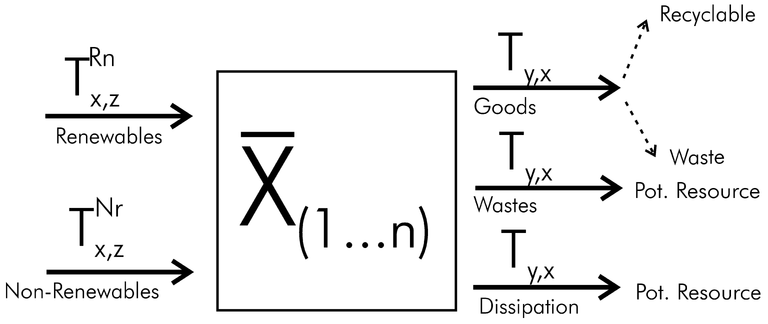

Figure 7: Exergy, for both matter and energy, may be split into renewable and non-renewable parts. For energy-related exergies, solar and wind power may be considered as renewable, whereas energy from fossil fuels may be considered non-renewable. For matter-related exergies, extraction of finite resources such as metals are considered non-renewable, while wood is a renewable resource.

Thus, it is seen that not all material or energetic fluxes have the same opportunities in addressing the issue of sustainability. We may therefore split these expressions further. One obvious way of addressing the problem is to divide in accordance with what is thought to be renewable versus non-renewable resources. This is illustrated in Fig. 7.

Splitting exergy or emergy fluxes in this manner strengthens the possibilities to investigate strategies for substitution, evaluation of reuse/recycle options, and so on and weigh them against availability and real environmental costs of resources.

7 A BASIC OPTIMISATION PROBLEM TO ACHIEVE SUSTAINABILITY

The problem of optimisation on the basis of holistic indicators like exergy or emergy is, as mentioned, the loss of information that occurs during aggregation. What is actually the right strategy for implementation of measures still needs to happen at a single process level for either of the two. All in all, we need an approach capable of capturing both the single individual processes or sub-aggregates (sub-suppliers) of the final product.

Considering an industrial system as a production unit receiving matter fluxes of energy and matter to the various process and production units and in the end giving them out to society (or the next) production unit as goods should pose no problems as demonstrated above.

The next step is to transfer the problem into mathematical formulation that may be optimised in a relatively simple manner. The easiest will be to transfer the matrix representation of the environ introduced above to the production situation. In Fig. 8, an initial split into four sub-matrices is introduced.

The upper part of the matrix deals with the material cycle(s) and the lower with energy-related conversions. Thus the outflow from the right side of the upper, material part is related to waste or reusable, recyclable material(s) and the lower to energy wasted as heat dissipation or a part that may eventually be used in other processes.

8 COUPLING EXERGY TO EMERGY

But energy, even if having the same quantity is not always equally good in performing work. Therefore, to optimize the performance, we should rather use a measure of this qualitative perspective,

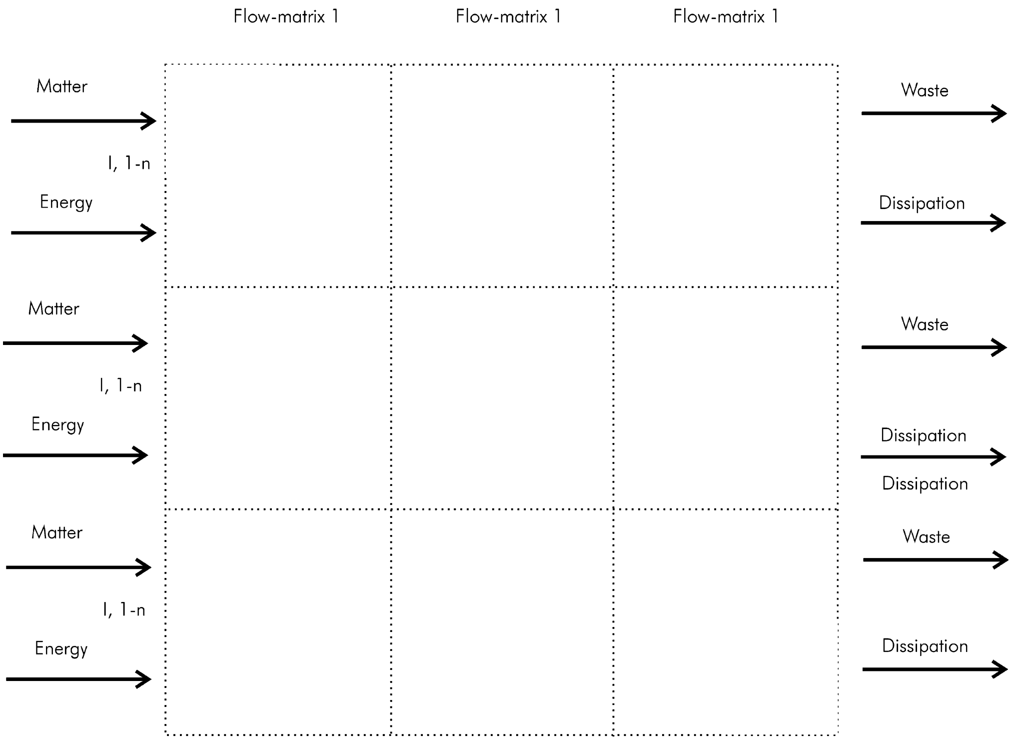

Figure 8: The environ split into more details. First, exergy or emergy is split into energy or matter-related parts. A split in renewable versus non-renewable resources is a subset hereof.

in this case we have chosen exergy. Exergy is already a well-established measure of energy quality, in the sense that it expresses how much work one may get out of a certain quantity of energy.

Meanwhile, the next logical step introduced is that energies are now valuated and balances established on basis of their respective exergetic contents. Exergy has for some decades now been used to evaluate and optimise the performance of various types of production systems.

The next step is the coupling to emergies and in particular the transformities of the process involved.

Both need to be coupled to various inputs of renewable and non-renewable resources to establish indices that may help indicate a direction of sustainability. This complicates the situation slightly but not into dimensions that any computer today will not be able to handle. This may be summarised by the depiction given in Fig. 9. This figure presents the situation in a three-dimensional manner which is thought to be ideal to summarise the problem.

Meanwhile, the problem may be transferred to a two-dimensional case, where the entire system is represented by one matrix. Such a matrix may be expanded as much as necessary depending on the complexity of the production process, or according to the emergy and exergy concept. An example is given Fig. 10.

In Fig. 10, the three-dimensional situation in Fig. 9 is simply represented in a two-dimensional manner leaving many of the sub-matrices void. Meanwhile, there will be some non-void places in the matrix corresponding to energy used by processing material(s), e.g. energy for melting or they may be used for entering transformities.

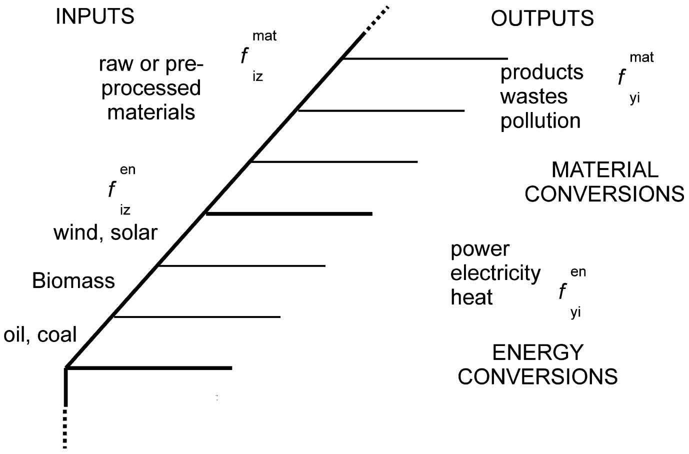

Figure 9: A matrix representation of Fig. 8 that now may include all energetic and material fluxes accounted for in exergy or emergy terms, renewable and non-renewable forms. For a whole production life cycle, the matrix may be huge but has the advantage of allowing many detailed efficiency indices to be established.

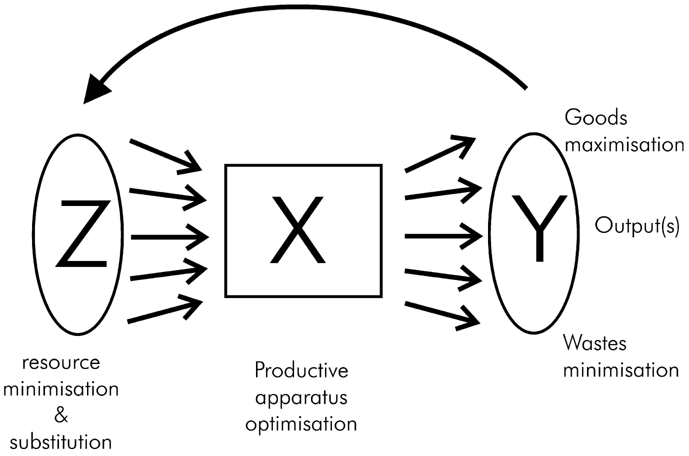

Figure 10: Cleaner production activities interpreted within the environ framework. Cleaner production activities will serve to decrease the burden on the input and output environ by means of activities as indicated by examples in the figure.

9 PERSPECTIVES

To summarize, the proposed strategy to implement exergy and emergy approaches in combination with an interpretation of the systems as environs seem to be fruitful. The strategy may be used in extended analysis of the energy efficiency of industrial systems, for instance, in connection to an LCA to be carried out. The strategy has several advantages:

1. material and energetic fluxes are comprised by the same unit;
2. exergy seems to be better in tracking the flows creating a structure both in the forward and the backward direction;

3. emergy expresses the accumulated energetic price of a structure and may be better in comparing between structures;
4. both will allow for various levels of aggregation – in terms of the ability to deliver one overall measure of a system – or to allow for 'mining' into detailed parts of a production system that may be of particular interest.

As the material and energy flows have the same units, we get rid off the currency problem that has always been a curse when comparing various approaches, like LCA, MFA, material input per unit of service (MIPS), and so on. At the same time, we bring the quality perspective inherent in exergy into the discussion. This means that we will have a greater chance of indicating where to take action in the systems. One important question may be answered by this: What are the exact losses and what are the chances of getting more work from the system? Cleaner production will aim at capturing exergy losses within a particular production environ, whereas industrial ecology will attempt to use still useful exergies within the same product life cycle or even between different product cycles.

Meanwhile, the integration does not free us from the necessity to make a choice between options where the evaluation of problems may become subjective in character, for instance, when deciding whether the CO_2 emission connected to a dissipative flux of energy is worse than an exergetic loss in a material flux of aluminium. In this case, we still need socio-economic considerations to come into play.

When comparing the two approaches in the manner presented here, it will seem that exergy reaches a more detailed analysis of the situation. This is probably not true as the calculation of the emergy content of a product or service detail demands just as high a level of knowledge about the various input emergies. Only more detailed knowledge tends to be excluded when overall evaluation of systems are presented. Thus, it will be possible to establish efficiency factors in just as detailed a level as that of exergy provided one has the information available.

Therefore, the major difference existing is that emergy focuses on the storage, the embedded content, whereas exergy flow analysis may be used to track how the emergy/exergy enters into a certain compartment. In this sense, both approaches look back into the input environ. But, in addition, exergy does look forward into the output environ. This is of high value as it allows us to evaluate the fluxes out of the system. This will serve to point out where the more valuable exergetic resources are lost. Those are the ones to be kept in the system by increased cycling and re-cycling of processes. This in turn proves that a technically feasible solution exists or should be evolved.

Structuring the analysis by means of matrices in the manner sketched above allows us to go into details within parts of the system or just to evaluate the system as a whole. To improve conditions in a production of a certain product by cleaner production, one will have to look for possibilities to create more cycling of high exergy fluxes, which for the time being leaves the system, by increasing recycling, i.e. creating new fluxes in the empty quadrants of the systems (again see Fig. 8). Industrial ecologists will attempt to create fluxes between systems in addition to the previous. In any of the cases, the approach may be used to forecast which initiative, cleaner production or industrial ecology, may be the more rational to implement in a particular case.

Having implemented the above-mentioned approaches and calculated indices it does not take much to couple the system to economics. The problem will only be what to be optimised and how. One major problem will be that investments and achievements in terms of savings of energy and matter and at the end prices of a certain product or service are not linearly correlated. Furthermore, prices of energy and materials are not stable through time as they are highly subject to the political situation, both on a national and a global scale. Accounting in terms of exergy is fairly easy, although the coupling at least at the microeconomic scale may be carried out [14, 47], it will probably be very difficult on a macroeconomic scale. Putting taxes on exergy consumption or dissipation though, as proposed by Szargut [41], will create an incentive to do something about it.

CONCLUSION

In the article, the environ concept of B.C. Patten [26] proposed and used for ecosystems has been transferred to production systems to organise the fluxes in the same manner as when used to analyse ecosystem fluxes. The environ concept is a highly consistent and robust approach and has been easily applied to production systems. It has been suggested to construct the energetic analysis on two measures, exergy and emergy, established quite recently. Exergy serves as an indicator of useful fluxes and how well they are used. Emergy serves to calculate the actual cost of a structure to be used for comparison of products. The method has been used to derive new indices more or less detailed in a degree of resolution. The indices can be used to decide where to put efforts to optimise systems in the most efficient way. The combined approach is thought to assist to achieve a more sustainable development of production systems and the society as a whole.

REFERENCES

[1] Bouman, M., Heijungs, R., van der Voet, E., van den Bergh, J.C.J.M. & Huppes, G., Material flows and economic models: an analytical comparison of SFA, LCA and partial equilibrium models. *Ecological Economics*, **32(2)**, pp. 195–216, 2000.

[2] Narayanaswamy, V., Scott, J.A., Ness, J.N. & Lochhead, M., Resource flow and product chain analysis as practical tools to promote cleaner production initiatives. *Journal of Cleaner Production*, **11**, pp. 375–387, 2003.

[3] Fratscher, W. & Stephan, K., Waste energy usage and entropy economy. *Energy*, **28**, pp. 1281–1302, 2003.

[4] Gaggioli, R.A., The concept of available energy. *Chemical Engineering Science*, **16**, pp. 87–96, 1961.

[5] Bakshi, B.R., A thermodynamic framework for ecologically conscious process systems engineering. *Computers and Chemical Engineering*, **26**, pp. 269–282, 2002.

[6] Wall, G. & Gong, M., On exergy and sustainable development – Part 1: Conditions and concepts. *Exergy, an International Journal*, **1**, pp. 128–145, 2001.

[7] Gong, M. & Wall, G., On exergy and sustainable development – Part 2: Indicators and methods. *Exergy, an International Journal*, **1**, pp. 217–233, 2001.

[8] Bloemhof-Ruwaard, J.M., van Beek, P., Hordijk, L. & Van Wassenhove, L.N., Interactions between operational research and environmental management. *European Journal of Operational Research*, **85**, pp. 229–243, 1995.

[9] van Berkel, R. & Lafleur, M., Development of an industrial ecology toolbox for the introduction of industrial ecology in enterprises – II. *Journal of Cleaner Production*, **5**, pp. 27–37, 1997.

[10] van Berkel, R., Willems, E. & Lafleur, M. Application of an industrial ecology toolbox for the introduction of industrial ecology in enterprises – I. *Journal of Cleaner Production*, **5**, pp. 11–25, 1997.

[11] Rosen, M.A. & Scott, D.S., Entropy production and exergy destruction: Part II – illustrative technologies. *International Journal of Hydrogen Energy*, **28**, pp. 1315–1323, 2003.

[12] Rosen M.A. & Scott D.S., Entropy production and exergy destruction: Part I – hierarchy of Earth's major constituencies. *International Journal of Hydrogen Energy*, **28**, pp. 1307–1313, 2003.

[13] Rosen, M.A. & Dincer I., Exergy as the confluence of energy, environment and sustainable development. *Exergy, an International Journal*, **1**, pp. 3–13, 2001.

[14] Wall, G., Conditions and tools in the design of energy conversion and management systems of a sustainable society. *Energy Conversion Management*, **43**, pp. 1235–1248, 2002.

[15] Odum, H.T., Self-organization, transformity, and information. *Science*, **242**, pp. 1132–1139, 1988.

[16] Odum, H.T., *Environmental Accounting: Emergy and Environmental Decision Making*, John Wiley & Sons Inc.: New York, 1996.

[17] Ulgiati, S. & Brown, M.T., Quantifying the environmental support for dilution and abatement of process emissions. The case of electricity production. *Journal of Cleaner Production*, **10**, pp. 335–348, 2002.

[18] Ulgiati, S., Brown, M.T., Bastianoni, S. & Marchettini, N., Emergy-based indices and ratios to evaluate the sustainable use of resources. *Ecological Engineering*, **5**, pp. 519–531, 1995.

[19] Odum, H.T., *Environment, Power and Society*, John Wiley and Sons: New York, 1971.

[20] Evans, R.B., Crellin, G.L. & Tribus, M., Thermoeconomic considerations of sea water demineralization. *Principles of Desalination*, ed. K.S. Spiegler, Academic Press: New York, pp. 21–76, 1966.

[21] Bastianoni, S., Marchettini, N., Panzien, M. & Tiezzi, E., Sustainability assessment of a farm in the Chianti area (Italy). *Journal of Cleaner Production*, **9**, pp. 365–373, 2001.

[22] Wall, G., Exergy conversion in the Japanese society. *Energy*, **15**, pp. 435–444, 1990.

[23] Wall, G., Exergy use in the Swedish society 1994. *Thermodynamic Analysis and Improvement of Energy Systems*, ed. C. Ruixian, Beijing World, Chinese Society of Engineering Thermophysics and American Society of Mechanical Engineers, pp. 403–414, 1997.

[24] Georgescu-Roegen, N., *The Entropy Law and the Economic Process*, Harvard University Press: Cambridge, MA, 1971.

[25] Bastianoni, S., Facchini, A., Susani, L. & Tiezzi, E., Emergy as a function of exergy. *Energy*, **32**, pp. 1158–1162, 2007.

[26] Patten, B.C., Systems approach to the concept of environment. *Ohio Journal of Science*, **78**, pp. 206–222, 1978.

[27] Higashi, M. & Burns, T.P., *Theoretical Studies of Ecosystems. The Network Perspective.* Cambridge University Press: Cambridge, UK, 1991.

[28] Russel, L.D. & Adebiyi G.A., *Classical Thermodynamics*. Saunders College Publishing: Philadelphia, PA, 1993.

[29] Bejan, A., *Advanced Engineering Thermodynamics*, 2nd edn, Wiley-Interscience: New York, 1997.

[30] Jørgensen, S.E., *Integration of Ecosystem Theories: A Pattern*, 2nd edn, Kluwer: Dordrecht, 1997.

[31] von Uexküll, J., *Theoretical Biology*, Harcourt, Brace & Company: New York, 1926.

[32] Odum, H.T., *Environment, Power and Society*. Wiley Interscience: New York, 1971.

[33] Odum, H.T., Pulsing, power and hierarchy. *Energetics and Systems*, eds W.J. Mitsch, R.K. Ragade, R.W. Bosserman & J.A. Dillon Jr, Ann Arbor Science, 1982.

[34] Bastianoni, S. & Marchettini, N., The problem of co-production in environmental accounting by emergy analysis. *Ecological Modelling*, **129**, pp. 187–193, 2000.

[35] Brillouin, L., *Science and Information Theory*. Academic Press, 1967.

[36] Dewulf, J., Van Langenhove, H., Mulder, J., van den Berg, M.M.D., van der Kooi, H.J. & de Swaan Arons J., Illustrations towards quantifying the sustainability of technology. *Green Chemistry*, **2**, pp. 108–114, 2000.

[37] Dewulf, J. & Van Langenhove, H., Quantitative assessment of solid waste treatment systems in the industrial ecology perspective by exergy analysis. *Environmental Science and Technology*, **36**, pp. 1130–1135, 2002.

[38] Dewulf, J. & Van Langenhove, H., Exergetic material input per unit of service (EMIPS) for the assessment of resource productivity of transport commodities. *Resources, Conservation and Recycling*, **38**, pp. 161–174, 2003.

[39] Szargut, J., Ziebik, A. & Stanek, W., Depletion of the non-renewable natural exergy resources as a measure of the ecological cost. *Energy Conversion and Management*, **43,** pp. 1149–1163, 2002.

[40] Szargut, J., Application of exergy for the determination of the pro-ecological tax replacing the actual personal taxes. *Energy*, **27**, pp. 379–389, 2002.

[41] Szargut, J., Sequence method of determination of partial exergy losses in thermal systems. *Exergy, an International Journal*, **1**, pp. 85–90, 2001.

[42] Szargut, J., Morris, D.R. & Steward, F.R., *Exergy analysis of Thermal, Chemical and Metallurgical Processes*. Springer: Heideberg, Germany, 1988.

[43] Sciubba, E. & Ulgiati, S., Emergy and exergy analyses: complementary methods or irreducible ideological options? *Energy*, **30**, pp. 1953–1988, 2005.

[44] Bastianoni, S., Nielsen S.N., Marchettini, N. & Jorgensen, S.E.J., Use of thermodynamic functions for expressing some relevant aspects of sustainability. *International Journal of Energy Research*, **29,** pp. 53–64, 2005.

[45] Sciubba, E., Beyond thermoeconomics? The concept of extended exergy accounting and its application to the analysis and design of thermal systems. *Exergy, an International Journal*, **1**, pp. 68–84, 2001.

[46] Milia, D. & Sciubba, E., Exergy-based lumped simulation of complex systems: An interactive analysis tool. *Energy*, **31**, pp. 100–111, 2006.

[47] Barbiroli, G. & Raggi, A., A method for evaluating the overall technical and economic performance of environmental innovations in production cycles. *Journal of Cleaner Production*, **11**, pp. 365–374, 2003.