

USE OF EXERGY ANALYSIS TO COMPUTE THE RESOURCE INTENSITY OF BIOLOGICAL SYSTEMS AND HUMAN SOCIETIES

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ABSTRACT

Exergy analysis (ExA) has a quite extensive history of successful applications in Engineering, and especially in the original niche in which it saw the light, Energy Conversion Systems. A vast body of literature confirms that a correctly formulated exergy approach leads to a better design, in that it helps identify and refine the configuration of systems that generate the desired outputs (conventionally called “products”, P) by the minimum feasible use of primary resources (conventionally called “fuels”, F). A similarly vast body of literature deals with the more fundamental aspects of the theory: where and how ExA improves a conventional energy analysis, how large is the attainable marginal improvement in the efficiency (P/F), what are the implications of these improvements, what is their theoretical significance (especially with regard to the so-called “sustainability issue”). When combined with the concept of “cost”, ExA has originated a novel and industrially relevant method, Thermo-Economics (TE), which expresses the monetary cost of P not in terms of €/kg or €/unit but in terms of €/(exergy content). TE led to interesting reassessments of “optimal” energy conversion chains, and did itself undergo a quantum leap when the innovative Ecological Cost (EC) theory was introduced to include one of the “costs of externalities” of P. EC expresses the production cost not on the basis of a monetary proxy, but of the amount of exergy in F needed to generate P. Obviously, both TE and EC are amenable to a genuine life-cycle analysis. Still, all of the above applications are limited to the study of engineered systems, which are usually designed on the basis of process diagrams that apply the concepts of Classical Equilibrium Thermo-dynamics and introduce proper corrections to model irreversible and non-equilibrium effects. But, unlike entropy, exergy does not require an extension of Classical Thermodynamics to be applied to non-equilibrium processes: if a system proceeds from whatever initial state S1 (equilibrium or non-equilibrium) to a final state S2 in which it is no longer capable of producing useful external work, the exergy is a well defined quantity, regardless of S1 being homogeneous or not, in local equilibrium or not. This peculiarity suggests that the current methods of exergy analysis may be extended to assess the “conversion efficiency” (P/F) of systems that are not amenable to a classical treatment: the extension discussed in this lecture deals with societal and biological systems. Societal systems are treated as complex non-homogeneous thermodynamic systems interacting with a conventional environment. On the basis of a sufficiently detailed exergy flow diagram, it is possible to relate a set of properly defined “products” (commodities, including money, labour, etc.), “wastes” (discharges) and “environmental impact” with the amount of primary exergy required to maintain the system at a certain pre-assigned state. The theory leads to the definition of an “embodied primary exergy content” called the *extended exergy cost* of P. Biological systems are treated in much the same way, with the *caveat* that the description is global (group, species, herd), and therefore is only valid for ensembles rather than for individuals. Here, too, it is possible to define a “species efficiency” as the ratio of the useful accumulated exergy to the total incoming exergy flow.

INTRODUCTION

When addressing issues related to “environmental interactions”, the difference between “anthropic” and “natural” systems fades: whenever a system A of either type interacts with an environment O, it can do so only by exchanging mass and/or energy through its boundaries, and such exchanges are ruled by the applicable laws of Thermodynamics and constrained by the applicable (internal and external, and possibly time-dependent) boundary conditions. Therefore we shall drop the distinction here. Another important consideration is that real systems are open: they either have permeable or/and perforated or/and diabatic or/and displaceable boundaries that allow exchanges of mass, heat and work with the “outside” against an externally imposed potential (concentration, temperature or pressure respectively). A common feature all systems of relevance display is their being -for a finite period of time- not in equilibrium: the study of “systems that have reached stable equilibrium” is actually of no interest to engineering sciences, because in such a state there can be no meaningful energy exchange; and arouses even

less interest in biological sciences, where “stable equilibrium” is synonym of “dead organism”. Thus, to understand the dynamics of systems behaviour, we must use non-equilibrium paradigms, in particular non-equilibrium Thermodynamics. We capitalize naturally on the large, well-established and very useful body of knowledge that “classical” or “equilibrium” Thermodynamics has contributed to create: only, the features of complex systems require some additional principles and tools to be described with sufficient (and operative) approximation. Non-equilibrium Thermodynamics is a relatively new field (a clear and rigorous review is offered in [19], and a discussion is provided in Panel B), and its topics are not as crisp as those of its equilibrium counterpart: we shall use here the following assumptions, which we posit without further justification:

- The systems of interest are not so far from equilibrium that catastrophic changes happen in their structure (in other words, they remain sufficiently far from any bifurcation words, they remain sufficiently far from any bifurcation point may exist in their phase space evolution);

- However complex the system, it is always possible to subdivide it in sufficiently small portions (subsystems) such that each one of them is in equilibrium (assumption of local equilibrium);
- Under the above stipulations, a property “temperature” can be defined for the system;
- Under the above stipulations, entropy is a state function for the entire system and for each of its sub-systems;
- The boundary conditions are not a variable in this study: they are specified once and for all by the problem position and can vary both in space- and in time¹;
- All properties of the system and of its environment can be described in terms of legitimate thermodynamic quantities.

In such a perspective, the representation of any system of interest for the present discussion is relatively simple (figure 1): a system A is in a certain configuration A_0 at an arbitrary initial time t_{init} , then exchanges a certain amount of mass and energy with its surroundings, “growing” and/or “shrinking” in space state, possibly in a pseudo-periodic fashion, until it reaches the end of our observation window at time t_{fin} , having reached a state A_{fin} not necessarily equal to A_0 . The equations ruling the evolution from t_{init} to t_{fin} are: mass conservation

$$\frac{dM}{dt} = \sum m_{in} - \sum m_{out} \quad (1)$$

energy conservation

$$\frac{dE}{dt} = \sum E_{in} - \sum E_{out} \quad (2)$$

entropy balance

$$\frac{dS}{dt} = \sum \dot{S}_{in} - \sum \dot{S}_{out} + \dot{S}_{irr} \quad (3)$$

exergy equation

$$\frac{dEx}{dt} = \sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} - \dot{Ex}_{\delta} \quad (4)$$

We are seeking a general expression for the evolution of the state of the system in time. The independent variables are the extensive quantities M, E, S and Ex, and since their respective initial values are known (A_0 must be well-defined for the analysis to be meaningful), the system of four equations in four unknowns appears well posed. The system of equations (1-4) must be closed by explicitly calculating the right-hand sides of either equation: let us examine in detail these input/output/generation/destruction terms.

a) Mass in- and outflows

Mass cannot be created in any of the sub-portions of A, and thus the variation in the total mass of A can only be given by the net material convection and diffusion flows through the boundary:

$$\begin{aligned} m_{in,conv,j} &= \int_b \rho_j v_{in,j} dA_b \\ m_{out,conv,k} &= \int_b \rho_k v_{out,k} dA_b \end{aligned} \quad (5)$$

Where $j=1\dots J$ and $k=1\dots K$ (J not necessarily equal to K) are the inlet and outlet “ports” on the boundary b where convection is allowed.

¹ This implies that the “surroundings” do not change appreciably their thermodynamic state as a direct consequence of their interaction with the system: any change in the state of the environment O is specified in advance for each case under consideration.

$$\begin{aligned} m_{in,diff,i} &= \int_b D_i \Delta c_{b,i} dA_b \\ m_{out,diff,l} &= \int_b D_l \Delta c_{l,b} dA_b \end{aligned} \quad (6)$$

Where $i=1\dots I$ and $l=1\dots L$ are the permeable portions of the boundary b , D are the diffusion coefficients and Δc are the concentration gradients across these portions. Substituting (5) and (6) into (1) closes the balance: however, it must be noted that the coefficients D in general depend on the diffusion dynamics across all other internal “layers” that contribute to mass diffusion inside of the system [10] (figure 2). Even in the oversimplifying assumption of the absence of chemical reaction inside of A, we need to solve a set of N “internal” diffusion equations for each chemical species, where N is the number of “diffusion exchanges” among sub-systems: this is though feasible numerically, with a degree of accuracy satisfactory for most practical cases, and therefore equation (1) can be considered “solvable”.

b) Energy in- and outflows

Energy is also globally conserved, and the variation in the total energy of A can only be produced by material and immaterial convection, and work done at the boundary:

$$e_{in,conv,j} = \int_b m_{in,j} h_{in,j} dA_b \quad (7)$$

$$e_{out,conv,k} = \int_b m_{out,k} h_{out,k} dA_b$$

$$e_{in,heat,j} = \int_b q_{in,j} dA_b = \int_b \Lambda_j \Delta T_{b,j} dA_b \quad (8)$$

$$e_{out,heat,k} = \int_b q_{out,k} dA_b = \int_b \Lambda_k \Delta T_{k,b} dA_b$$

$$e_{in,work,j} = \int_b \Delta p_{b,j} \square dx_{b,j} dA_b \quad (9)$$

$$e_{out,work,k} = \int_b \Delta p_{k,b} \square dx_{b,k} dA_b$$

The physical meaning of the above equations is simple: every elementary portion of incoming or outgoing mass carries an energy content equal to its enthalpy²; heat in- and outfluxes can be expressed as product of an equivalent transmittance of the system/environment interface times an appropriate temperature difference across each diabatic portion of the boundary³; work can be expressed as an “equivalent force” due to a local pressure difference at the boundary times the local displacement of the boundary in the direction of the (local) normal versor.

c) Entropy in- and outflows, irreversible entropy generation

The entropy balance can be derived along the same line of reasoning: neglecting here again the contribution of chemical reactions, the variation of the total entropy of A is the result of material and immaterial convection, heat exchange at the boundary, and entropy generation inside of A:

$$s_{in,conv,j} = \int_b m_{in,j} s_{in,j} dA_b \quad (10)$$

$$s_{out,conv,k} = \int_b m_{out,k} s_{out,k} dA_b$$

² Total enthalpy, if we include kinetic energy (often negligible in practical cases)

³ By selecting proper expressions for \square and $\square T$, this simple formalism can be used to include heat exchanges due to convection and radiation.

$$s_{in,heat,j} = \int_b \frac{q_{in,j}}{T_{in,j}} dA_b = \int_b \frac{A_j \Delta T_{b,j}}{T_{in,j}} dA_b \quad (11)$$

$$s_{out,heat,k} = \int_b \frac{q_{out,k}}{T_{out,k}} dA_b = \int_b \frac{A_k \Delta T_{b,k}}{T_{out,k}} dA_b$$

$$\dot{S}_{irr} = \dot{S}_{ext} + \int_{V_A} \sigma dV \quad (12)$$

The physical meaning of the above equations is also clear: every elementary portion of incoming or outgoing mass carries an entropy content; heat in- and outfluxes contribute to the global entropy balance each according to an appropriate temperature difference across the respective diabatic portions of the boundary; and the irreversible entropy generation consists of two terms: the first is purely internal and takes place over the entire volume of A, while the second accounts for possible effects of A on the surroundings.

d) Exergy in- and outflows, exergy destruction

Exergy is not a conserved quantity, but its equation can be written in a “conservative form” by introducing a fictitious term, the *exergy destruction*, which is not a physical flux but rather a convenient mathematical artefact. However, this exergy destruction does have a physical meaning, in that it measures the energy degradation (dispersion) in the process. Neglecting again the contribution due to chemical reactions, we have:

$$ex_{in,conv,j} = \int_b m_{in,j} ex_{in,j} dA_b \quad (13)$$

$$ex_{out,conv,k} = \int_b m_{out,k} ex_{out,k} dA_b$$

$$ex_{in,heat,j} = \int_b f(T_{in,j}, T_0) q_{in,j} dA_b = \int_b f(T_{in,j}, T_0) A_j \Delta T_{b,j} dA_b$$

$$ex_{out,heat,k} = \int_b f(T_{out,k}, T_0) q_{out,k} dA_b = \int_b f(T_{out,k}, T_0) A_k \Delta T_{k,b} dA_b \quad (14)$$

$$ex_{in,work,j} = \int_b \Delta p_{b,j} dx_{b,j} dA_b \quad (15)$$

$$ex_{out,work,k} = \int_b \Delta p_{k,b} dx_{b,k} dA_b$$

The factor f is the so-called exergetic factor, and takes a different form for conduction/convection (for which it is equal to the Carnot factor $1 - T_0/T_j$) and radiation (for which it is equal

$$\text{to } 1 + \frac{\left(\frac{T_0}{T_j}\right)^4}{3} - \frac{4T_0}{3T_j} \quad [22]).$$

Equations (5-15) reveal by inspection the difficulty in closing the system of equations (1-4): even in the assumption of perfectly specified boundary conditions, the general balance equations depend on the *internal behaviour* of the system, because the rates of mass and energy exchange are dictated not only by the “layer” of the system that is in immediate contact with the environment through its boundary, but from the interactions among the internal “cells” in which we imagine to subdivide A. This suggests that a “lumped” treatment may be more appropriate for a useful description of the system’s behaviour.

THE EXERGY COST OF A PROCESS

Let us consider the exergy flow diagram of the system under study (figure 3): we shall follow Tsatsaronis’ notation [34], and

denote by “F” the exergy inputs, by “P” the “products” of the system, and by “W” its byproducts (unused discharges into the environment): from the exergy equation we derive a measure of the exergy destruction (overdots omitted from now on):

$$Ex_{\delta}(t) = F(t) - P(t) - W(t) \quad (16)$$

With the additional stipulation that P(t) includes the “products” internally incorporated by A at time t , i.e., those that contribute to its growth: conversely, a positive difference between W(t) and P(t), for a fixed F(t) denotes a “shrinking” system. At any instant t , the conversion efficiency of A is given by:

$$\eta_A(t) = \frac{P(t)}{F(t)} \quad (17)$$

And the exergetic cost of the products is the reciprocal of the efficiency:

$$c_A(t) = \frac{F(t)}{P(t)} \quad (18)$$

Thus, provided we have a complete knowledge of the input flows F and of the instantaneous mode of operation of A, equation (18) provides a measure of how many exergy “units” of fuel are embodied in every exergy unit of product.

Since it is unlikely that all “fuels” reach the boundary of A directly from the environment, without any previous treatment, it is necessary to backtrack the production process of each one of them, to compute its own exergy cost: this backtracking comes to a halt when all inputs have been assigned a valid equivalent primary exergy value (content). This procedure was proposed by Szargut [32] and results in the calculation of the Cumulative Exergy Content (CEC) of a product: provided a sufficiently disaggregated database is available, equation (18) can be computed at any instant of time. The “cost” thus calculated represents *the amount of primary exergy “embodied” in the product*, and is a rational measure of the load placed by A on the environment at any instant of its (technical or real) life.

But the picture is not yet complete: some of the effluents (cumulatively represented by the flux W) may be discharged in a physical state different than their respective “environmental conditions” (for example, they may consist of a material discharge at $T \neq T_0$ and $c \neq c_0$). This poses an additional “load” on the environment, which must use a portion of the primary exergy it can avail itself of (chemical, kinetic, radiative...) to exert some buffering action and reduce each discharge to its environmental state. The amount of exergy necessary for the buffering can be calculated if we know the processes involved: if a chemical reaction is required, its activation exergy is the additional cost; if a heat exchange is needed, the exergy of the corresponding amount of thermal exergy is the cost, and so on. If the system under consideration is artificial (of anthropic origin), a substantial portion of the effluent treatment is enforced by means of technical “pollution abatement” devices located downstream of the main process: here, the calculation of the extra exergy cost (called *environmental remediation cost*) requires an additional process analysis of the effluent treatment system: since technical pollution abatement is never complete, but inevitably relies on some amount of environmental buffering, the “technical” cost c must usually be augmented by the cost c' of the residual treatment performed by the biosphere. In principle, it is always possible to calculate this additional exergy requirement F'^4 that must be considered as an added cost of the product P:

⁴ In real cases, the calculation of F' is not so simple as represented here, because the “remedial action” takes place not at time t , but with an obvious delay: we shall neglect this effect here, and consider that F' can be “allocated” properly over the relevant time windows.

$$c_{tot,A}(t) = c_A(t) + c'_A(t) + c''_A(t) = \frac{F(t)+F'(t)+F''(t)}{P(t)} = \frac{F_{tot}(t)}{P(t)} \quad (19)$$

THE CONCEPT OF EXTENDED EXERGY

The cost defined by equation (19) is expressed in units of $\text{kJ}_{\text{fuel}}/\text{kJ}_{\text{product}}$, and constitutes a significant indicator of environmental load: if a product P is generated by two different production chains A_1 and A_2 , the one with the lower value of the $\int c_{tot}(t)dt$ over its entire lifetime is the more environmentally benign (less unsustainable) process. Notice that the rather simple considerations developed so far result in a proper internalization of the so-called *environmental externalities*, whose exergy cost is reallocated to the products of A.

In technical systems, the economic side must also be taken into account: several methods exist, and the most rigorous from a thermodynamic point of view is the Thermo-Economic costing, in which a monetary cost is assigned to the unit of exergy of fuels, products and discharges. [2,13,18,35,36,37 and in other papers in this Panel] present a complete and rigorous treatment of the underlying theory and demonstrate several engineering applications. The approach we propose here is though somewhat different: since the cost expressed by equation (19) represents the primary equivalent exergy embodied in the product and already includes the environmental externality, is it possible to devise a similar treatment for the remaining externalities, namely Labour and Capital? The answer is affirmative, and the method, called Extended Exergy Accounting (EEA), has been presented and discussed in several papers [25,26,31]. EEA computes the primary exergy equivalents of Labour (ee_L , in $\text{kJ}/\text{workhour}$) and Capital (ee_K , in $\text{kJ}/\text{€}$) on the basis of two econometric coefficients: the first (α) is derived from the *pro-capite* exergy consumption in the society within which the technical process A is operating and the second (β) from the society capital intensity, measured by a monetary circulation indicator, usually M2 (also called “money plus quasi-money). Though the procedure adopted in EEA to calculate the primary equivalents of Labour and Capital has been subjected to some criticism, we shall not address this point in the present discussion, and not delve into the numerical values of these equivalents, but assume that they can be calculated in an accurate and reproducible way [25]. Once $c_L=f(ee_L)$ and $c_K=f(ee_K)$ are known, both labour and capital expenses can be expressed in primary exergy units and included in the exergy flow diagrams as “fuels”: the final result is that an extended exergy cost can be assigned to any product P:

$$c_{ee,A}(t) = c_A(t) + c'_A(t) + c''_A(t) + c_L(t) + c_K(t) = \frac{F_{tot}(t)+F_L(t)+F_K(t)}{P(t)} \quad (20)$$

The extended exergy cost defined by equation (20) is based solely on thermodynamic concepts, and is the most comprehensive indicator of environmental load: it includes the total amount of primary exergy embodied in the product, including the production chain “from mine to dump”, and considering also the equivalent primary exergy required by the workers’ consumptions standards. It can therefore be regarded as the *exergy footprint* of product P, a rigorous EI measured in

kJ/kJ and rooted both in system analysis and thermodynamic principles.

Obviously, the approach just described identifies c_{ee} as a *global* EI, because the environmental effects it considers concern the entire production chain and thus a large portion of the biosphere (the mine can be located very far away from the conversion plant, and the latter very far away from the final user, so that the environmental impact that must be remedied affect areas only remotely connected with the location where the product is used). But in a broader vision of a globally interconnected biosphere [4,17] it is clear that c_{ee} can be correctly applied to the analysis of systems also at a local scale. In the EEA method, it suffices to have access to a properly disaggregated database that allows for the calculation of the CEC of all the “fuels” entering the system under consideration. If such a database is not available, the non-negligible effort necessary to compute these CEC anew brings a substantial payback, in that it leads to a consistent and rigorous calculation of the total environmental load placed by the system on the environment. For anthropic systems, yet an additional complication is posed by the calculation of the primary exergy equivalents of Labour and Capital (ee_L and ee_K), but again the benefit in terms of the reproducibility and of the coherence of the approach is more than worth the effort. EEA analyses of several individual processes and industrial/societal sectors have been performed in the last few years, and they consistently lead to a deeper insight of the exergy dynamics sustaining the system operation. Most of the published studies of the more complex systems were performed at steady state, due to the difficulty of obtaining reliable time series for the large amount of data needed for the analysis, but as the database is incrementally augmented, it becomes possible to attempt comparative studies about non-steady situations.

METHODOLOGY

The calculation of the follows the same lines as any exergy analysis, with a couple of additional steps:

- Obtain a detailed exergy flow diagram of the system (mass and energy balances are a required input);
- Compute the CExC of all the fuels. For imports (e.g., electricity imported from another country) the respective production chain must be analyzed;
- Derive the econometric coefficients necessary for the calculation of ee_L and ee_K . For imports (e.g., materials imported from another country), the econometric coefficients must refer to the country of origin;
- Add the costs of externalities. For fuels, simply add the terms $L*ee_L$ and $K*ee_K$ to the CExC, where L are the total workhours and K the capital involved in the production of the fuel. For the environmental cost, add for each effluent the product of its respective c' and c'' by the effluent exergy.

EXAMPLES OF APPLICATION

As previously mentioned, several applications of the EEA method have been published in the archival literature. Processes assessed or re-assessed by means of an EEA analysis include the analysis of an academic institution [3]; the analysis of a transient in a gas turbine plant [5]; the production process of a commercial truck [7]; an innovative CO_2 capture process [8]; gas-flaring in oil extraction [12]; a comparison of different desalination technologies [15]; the nuclear fuel extraction and

processing [21]; a comparative study of six different methods of hydrogen production [24]; biodiesel recovery from spent oils [33]. Additionally, EEA analysis of societal systems were published for China [6]; the Chinese transportation and agricultural sectors [9]; Norway [14]; England [16]; Italy [20]; the Netherlands [23]; the Turkish transportation and wastewater sector [30]; Turkey [31]. More recently, EEA analyses of living systems have been performed [28,29].

All applications demonstrate that the EEA results provide additional insight in the thermodynamic intensity of the internal flows in a process (or in a society) and result in useful information about possible improvements that may be obtained by reducing the primary exergy consumption for a prescribed output. The exergy cost indicator c_{ee} defined above represents therefore a proper Environmental Indicator (the use of C_{ee} as an *exergy footprint* was proposed for it [27]) and its use ought to be encouraged in the assessment of alternative scenarios towards a lower degree of unsustainability.

CONCLUSIONS

An elementary lumped analysis of a generic energy conversion system, intended in its broadest sense of “any system that operates by converting energy forms into one other”, performed by means of an exergy analysis paradigm, leads to the conclusion that from a technical point of view it is always possible to calculate the primary equivalent exergy embodied in a product or products: an exergy cost is defined as the ratio of the total embodied exergy to the cumulative production, in a life-cycle sense (i.e., integrated over time and space). Then, on the basis of the assumption that the equivalent primary exergy content of the remaining externalities (Labour and Capital) can also be computed, a novel indicator, the extended specific exergy cost c_{ee} , is defined. This indicator possesses all the requisites requested of an Environmental Indicator, and -while including *global effects*- it can be applied at a *local level*, to assess and compare individual processes, industrial sectors or entire societies. This indicator represents a useful and thermodynamically correct measure of the absolute (primary) consumption of exergy in a process, and may therefore be used as a measure of the degree of unsustainability of the process itself.

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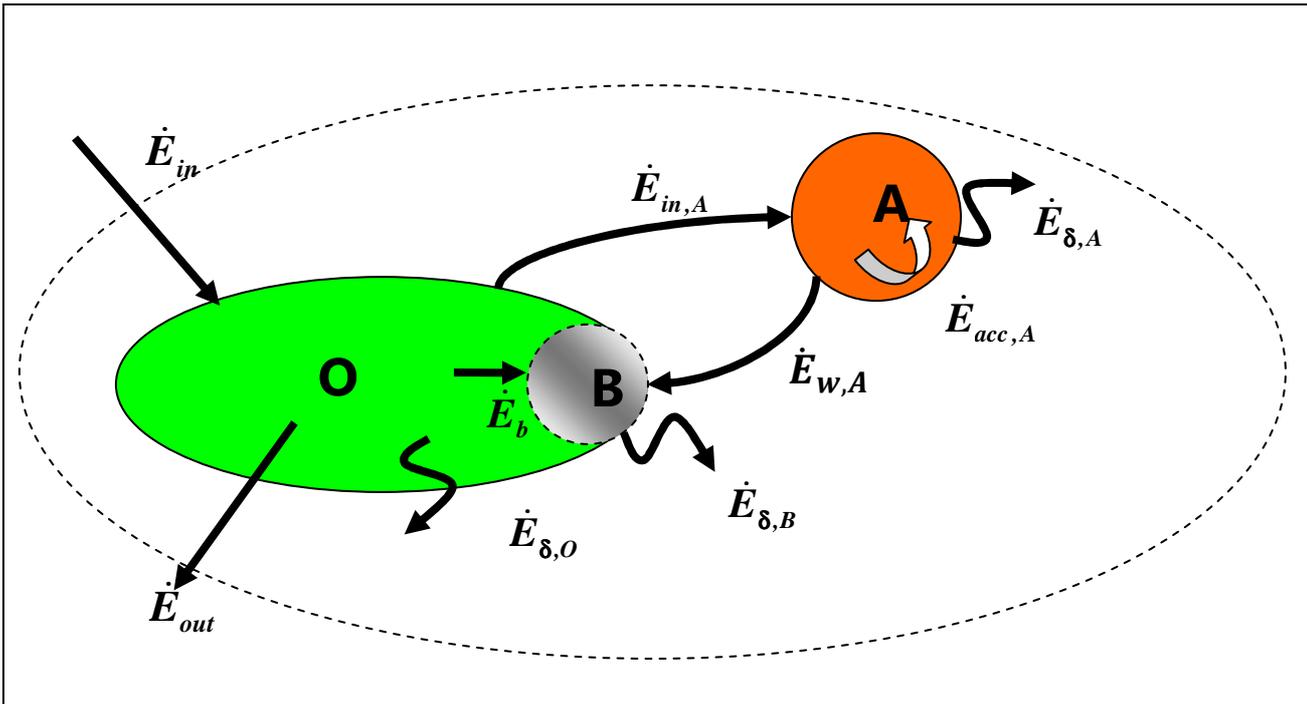


Figure 1 – Possible evolution of a system A interacting with a reference environment O

Legenda: O=reference environment; B=buffering portion of O; E_{in} , E_{out} =net exergy input and output in O; E_b =buffering exergy (see text); $E_{in, A}$ =exergy flux from O to A; $E_{acc, A}$ =exergy accumulation rate in A; $E_{w, A}$ =exergy discharge from A; E_{δ} =exergy destruction rate

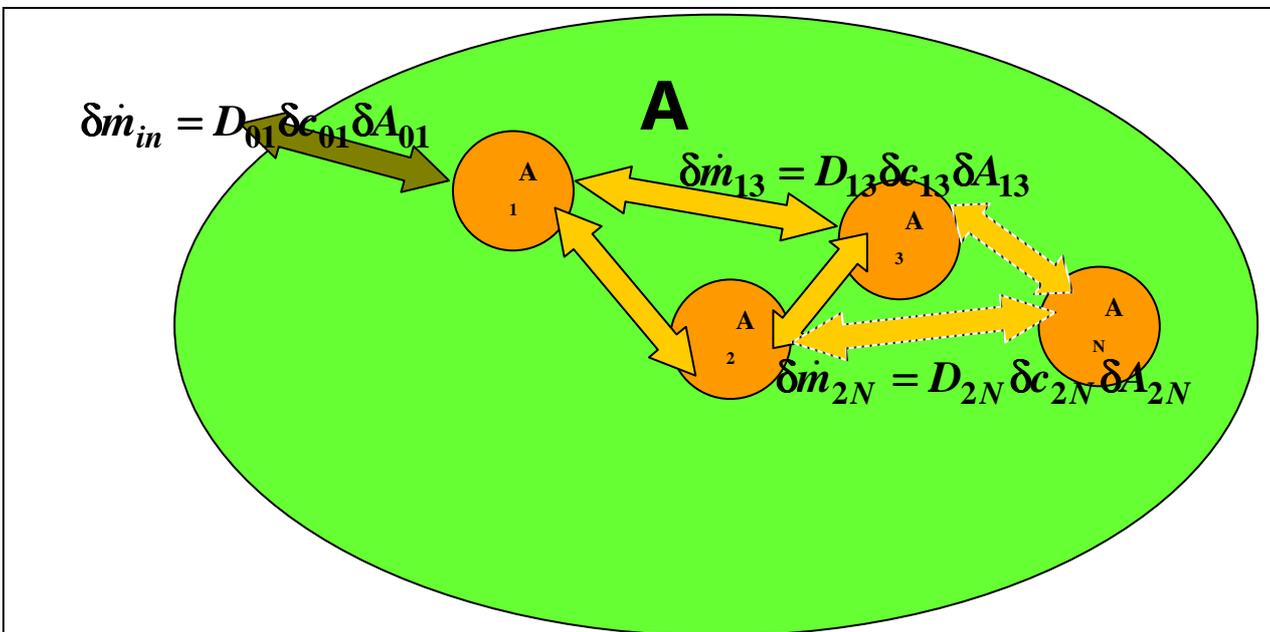


Figure 2 – Schematic representation of internal complex diffusion chains

Legenda: δA_{ij} = permeable contact area; δc_{ij} = concentration gradient; D_{ij} = Diffusion coefficient

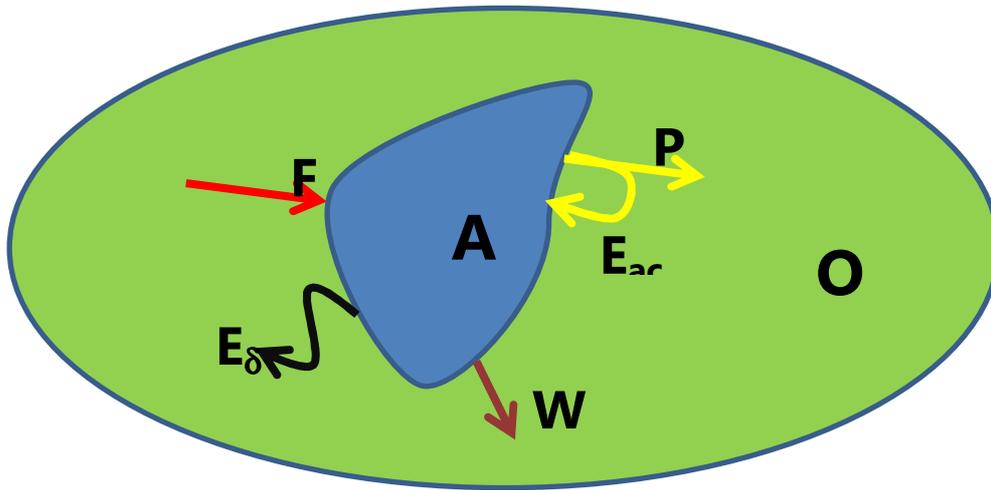


Figure 3 – Exergy flow diagram for a generic system