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THERMODYNAMICS AND SUSTAINABILITY A NEW APPROACH BY EXTROPY

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Abstract

This paper introduces and develops a new formulation of the Second Law for open systems by a new concept, extropy. Extropy is a non-equilibrium entropy potential, and it provides a calculable physical measure of the human impact on environment and formulates the physical limits of economic growth. By extropy thermodynamics will be a vital tool for the selection of a sustainable path.

Keywords: thermodynamics, sustainability, entropy, exergy.

1. Introduction

The importance of constraints imposed by thermodynamics on economic processes is well known in environmental economics (BARANYI [1], FABER et al [2], FAUCHEUX and NOËL [3], JANKOVICH [4], Kümmel [5], Månsson [6], O'Connor [7], RUTH [8] and VANHOVE [9]. The question addressed to thermodynamics is summarized in the question: Is it ethic to do the room?

The closed system approach answers: Every natural process is accompanied by an increase of entropy, says the Second Law. Every human action results in an excess entropy production. When I do the room of my daughter I create a higher degree of order there, while simultaneously I increase total entropy. She will have a nicer room. The price of it is garbage and a more entropic Universe. The more I do the room, the quicker we reach the heat-death state. So my daughter will live in a worse world. This simple formulation of the entropy law suggests that the higher the entropy the less valuable the world. When the higher entropy Universe means that she will live in a world of lower quality, then I have to stop or at least minimize my efforts. The same argument is valid for economic activities or production, too. When the present production and consumption diminishes the possibility of our future production and consumption then we sacrifice our grandchildren's future for present needs. We cannot do anything else, than to slow down the level of economic activities and thus postpone the devil's day.

The open system approach to the thermodynamic constraints results in just the opposite conclusion. The entropy production is obligatory for the steady state of the Earth. Low entropy energy comes from the Sun and it is irradiated with high entropy. Entropy of the Earth would decrease if there were no continuous entropy production present. To maintain the steady state, the total natural and human entropy production must become equal to the difference between the incoming and outgoing entropy fluxes. Our entropy production itself does not lead to an unsustainability. If we do not produce the entropy, then some other mechanism will ensure it. The more entropy we produce the stronger and powerful we will be! The real message of thermodynamics is to maximize the entropy production!? We have to use all the possibilities, otherwise somebody (or something) else will use it, or it will be lost.

The above argument would have been popular 50 years ago. The maximum power principle fits the ideology of the industrial age, but it does not fit the postmodern age. Following Word War

II industrial countries accepted economic growth, the doctrine of general welfare and mutual gauge of betterness among them. The higher the increase of GNP the better the economy. The higher the GNP the higher the material throughput of the economy. We have the feeling that higher GNP goes together with higher entropy production. So the higher the total entropy production the better the economy. Actually not so much was achieved in real welfare terms, the model of economic growth and industrialization was given the highest priority in developing countries, leaving aside the real needs of the majority of the population. The ecological consequences of the economic growth remained unnoticed until such publications as Rachel CARLSON's Silent Spring [10] and the MEADOWS' report to the Club of Rome [11], and the report of the BRUNDTLAND commission [12]. They succeeded in ringing the alarm bells by asserting that continuous economic growth is a self-destructive aim, which, because of its ruinous effect on environment, could not lead to any sustainable development. The report, however, puts forward the argument that the environmental problems caused by the economic growth can be resolved by accelerating such growth. In other words, the cause eliminates the consequence if the cause is reinforced enough [13].

The two simple answers of thermodynamics for the sustainable development are contradictory. The closed system approach yields a pessimistic world view of 'the forever decline', while the open system view (in this simplified form) ensures the modern age ideology 'we are obliged to increase to maximum the entropy production—that is our material welfare'. Both answers contradict common sense. The extropic formulation of thermodynamics yields a compromise, and tools which can be used to find a sustainable path.

2. Thermodynamics

The entropy principle is the product of a long attempt to find an adequate quantitative expression defining the directional properties of natural or spontaneous processes. The time arrow is formulated so that the entropy never decreases within an isolated system. The great success of the entropy approach is classical thermodynamics. A theory describing systems in equilibrium or undergoing reversible processes, which is particularly applicable to isolated systems, or to systems with isolation (walls). In isolated systems the equilibrium state is characterized by entropy maximum. If there is no thermal insulation, then $F = E - TS$, the free energy minimum is for the equilibrium state. If the wall is not fixed, then $G = E - TS + pV$ is minimum.

We consider an open system in a reservoir with T_0, p_0 and μ_0. There is no equilibrium thermodynamic potential characterizing the final equilibrium state of the system, as the thermodynamic approach suggests

$$B = E - T_0 S + p_0 V - \mu_0 N \tag{1}$$

or

$$BS = \frac{E}{T_0} - \frac{p_0}{T_0}V - \frac{\mu_0}{T_0}N - S = \sum_i Y_{io} X_i - S, \tag{2}$$

where Y_i is the i-th entropic intensive variable, while X_i is the i-th extensive one. In equilibrium state both of them equal zero, reflecting the fact that in an equilibrium state of an open system the internal parameters are fully determined by the external ones. B and BS are non-equilibrium thermodynamic potentials. Thermodynamic processes are governed by the $\Delta B < 0$ relation. B and BS have minimum values in equilibrium state.

The need for the application of B and BS was already recognized in the 19th century. P. G. TAIT [14] wrote: 'It is very desirable to have a word to express the Availability for work of the heat in a given magazine; a term for that possession, the waste of which is called Dissipation. Unfortunately the excellent word Entropy, which Clausius has introduced in this connection, is applied by him to the negative of the idea we most naturally wish to express. It would only confuse the student if we were to endeavor to invent another term for our purpose. But the necessity for some such term will be obvious from the beautiful examples which follow.'

B is already used, called exergy or essergy. The name exergy (German: 'Exergie') arose first among German power station and refrigeration plant engineers. A Slovenian engineer, Z. Rant proposed the word 'Exergie' in 1953 in Lindau (see SZARGUT [15]). The preliminary forms of essergy appeared in the literature earlier. In analogy to the Gibbs' free energy an available energy is defined for systems in a given environment (T_0, p_0), as

$$\Phi = E + p_0 V - T_0 S, \tag{3}$$

The function Φ was already proposed in the previous century by Maxwell and Gouy. Exergy is widely used in the engineering practice as a very useful tool for investigating the plants for efficiency (see: Pennti MALASKA [16])

SZARGUT [15] gave the following definition for exergy: 'Exergy is the amount work obtainable when some matter is brought in a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interactions only with the above mentioned components of nature.' Essergy [17] is the theoretical maximum useful work that is obtainable from a well-defined quantity of matter by bringing it to thermodynamic equilibrium with its surroundings. In this definition, it is assumed that the surroundings are capable of supplying or absorbing unlimited amounts of heat at temperature T_0 and of doing or receiving unlimited amounts of expansion work at pressure P_0. The maximum available work is calculated by comparing the initial and final equilibrium states. The initial state is characterized as follows:

- The environment is an equilibrium system, with temperature T_0, pressure p_0 and chemical potentials μ_{i0}.
- The system is characterized by its energy, E, entropy, S, volume V and by the mole numbers N_i.

The entropic non-equilibrium potential was introduced for the purpose to develop a method for the evaluation of entropy balances for industrial processes. In the previous papers it was called Π-potential, *Pi* for physical information [18]. The name extropy is introduced to emphasize its intimate relation with exergy [19]. The advantages of the use of extropy instead of entropy are as follows:

- for the determination of its numerical value measurable physical quantities are sufficient. Extropic evaluation of industrial processes can be done [20, 21].
- The Second Law constraints for economic and biological processes will be more transparent. The results show that the inflating Universe is creating extropy. The balance for Earth offers a thermodynamic foundation for the GAIA hypothesis [22].

For human activity two important consequences follow, namely: human entropy production is obligatory, but the right level is not simple maximization or minimization but optimization. For the wastes a thermodynamic measure is proposed, the total waste extropy measures the physical and chemical changes due to human activity. It is a measure of ecotoxicity.

3. Extropy

CLAUSIUS created the word entropy [23]. The root is the Greek word 'tropy' meaning 'transformation'. A small change of entropy is defined as being equal to the reversible flow of heat into the system, divided by the temperature of the system, i.e.,

$$\Delta S = \int\limits_{\text{reversible}} \frac{\delta Q}{T}, \tag{4}$$

where δQ is the heat transferred to the system at temperature T. In real processes the entropy increase is always higher than the thermal term, i.e.,

$$\Delta S \geq \int \frac{\delta Q}{T}, \tag{5}$$

and the equality sign is valid only for reversible processes. The difference is called entropy production, σ [24].

$$\Delta S - \int \frac{\delta Q}{T} = \sigma, \tag{6}$$

σ can never be negative. Positivity of σ expresses the unidirectionality of spontaneous changes. σ is the 'time arrow'. Entropy production is a measure of changes. When nothing happens σ is zero. $\sigma > 0$ is a sign that something happened. In an isolated system the future changes are measured by the integral of entropy production:

$$\Delta S = \int_t^\infty \sigma \, dt = S_0 - S, \tag{7}$$

where S_0 is the equilibrium entropy. The difference of the equilibrium value of entropy and the actual one is the total future entropy production, we call it extropy, Π. For an open system in a reservoir the total future entropy production will be

$$\Pi = \int_t^\infty \sigma \, dt = S_{s0} + S_{e0} - S_s - S_e, \tag{8}$$

where S_s is the entropy of the system, S_e that of its environment, while index $_0$ refers to the equilibrium state. Simple manipulations yield, that

$$\Pi = \sum_{ik} \int_{Y_i}^{Y_{i0}} (Y_{i0} - Y_i) \, dX_i. \tag{9}$$

or introducing the entropy matrix:

$$g_{ik} = -\frac{\partial^2 S}{\partial X_i \partial X_k} \tag{10}$$

and $s_{ik} = g_{ik}^{-1}$, we can write $dX_i = -s_{ik} dY_k$, so

$$\Pi = \sum_i \int_{Y_i}^{Y_{i0}} (Y_{i0} - Y_i)\, s_{ik}\, dY_k \tag{11}$$

Extropy is zero in the equilibrium state with the environment. $\Pi = 0$ means that the system is not distinguishable from its environment. There is no way to get energy from it. There is no order. The above definition can be extended to non-equilibrium systems with the local equilibrium hypothesis [25]. We divide the total volume of the system into small volumes v_α, the volume v_α being sufficiently small that, within it, the intensive properties T, p, and μ_i are virtually equal at all points, but on the other hand, these volumes are large enough to make the influence of fluctuations negligible. In this case the extropy of the system is the sum of the extropies of the parts.

$$\Pi = \sum_\alpha \Pi^\alpha . \tag{12}$$

The extropy is a function of the parameters of the reservoir, and the parameters of the system

$$\Pi = \Pi(T_0, p_0, \mu_{i0}, T, \mu_i, V). \tag{13}$$

The time dependence of extropy arises from the change of the reservoir and from the change of the system. The changes of T_0, p_0, μ_0 are crucial questions for sustainable development, but this question is beyond the scope of the present paper. We assume that the reservoir does not change.

$$\frac{d\Pi_{int}}{dt} = \frac{dS_0}{dt} - \frac{dS}{dt}, \tag{14}$$

where dS_0/dt describes the global change in the system + environment. It defines how the final entropy changes due to interactions with the outside world. Thermodynamics prescribes the balance equations for the entropies

$$\frac{d(S_s + S_{env})_0}{dt} = \sum_i Y_{i0} \frac{dX_i}{dt} = \sum_i Y_{i0} J_i, \tag{15}$$

where Y_{i0} is the value of the i-th intensive variable in the reservoir, while J_i is the net flow of the i-th extensive variable.

The actual value of the environment's entropy changes as:

$$\frac{dS^{env}}{dt} = \sum_i Y_{i0} J^{es}{}_i . \tag{16}$$

The actual value of the system's entropy changes as:

$$\frac{dS^s}{dt} = \sum_i Y_i J_i + \sum Y_i J_i^{se} + \sigma, \tag{17}$$

where σ is the internal entropy production, and $\sigma >= 0$, because of the Second Law of thermodynamics. The second term is the effective entropy flow (associated with materials/energy fluxes) across the system boundary from the outside world. The first term is the entropy flow between the system and the reservoir. Summing up the terms, one gets:

$$\frac{d\Pi}{dt} = \sum_i (Y_{i0} - Y_i)J_i - \sum_i (Y_{i0} - Y_i)J_i^{se} - \sigma. \tag{18}$$

The first term can be rewritten as the difference between the inflow and outflow of extropy. Extropy inflow/outflow is the extropy of the incoming/outgoing material and energy flow.

$$\Pi_{in} = \sum_{i,input}^{n} (Y_{i0} - Y_i)J_i. \tag{19}$$

Π_{in} is the incoming extropy flow, while Π_{out} is the outgoing one.

$$\Pi_{out} = \sum_{i,output}^{n} (Y_{i0} - Y_i)J_i. \tag{20}$$

The second term is the entropy production due to the equilibration processes between the system and reservoir. We introduce the total entropy production as

$$\Sigma = \sum_i (Y_{i0} - Y_i)J_i^{se} + \sigma. \tag{21}$$

The extropy balance equation is therefore

$$\Delta\Pi = J_{\Pi,in} - J_{\Pi,out} - \Sigma. \tag{22}$$

In a steady state $\Delta\Pi = 0$. Hence the entropy production in a steady state is just equal to the net extropy flow (inflow minus outflow). The extropy content of a system can be increased only by means of materials/energy exchanges with other systems. A system can only receive, destroy or transform extropy. In other words, a system cannot spontaneously create extropy. If all the extropy in a system is lost (consumed), there will be no further potential for change.

The entropy production can be written as:

$$\sigma = \sum_{i,k} L_{ik}\delta Y_i \delta Y_k, \tag{23}$$

where L_{ik} is the conductivity matrix, being positive definite. In the temperature difference case, it is the heat conductivity; in case of voltage difference it is the ohmic resistance. The two matrices, L and s are independent, but it is a general rule that in stable systems they are simultaneously positive. A very important consequence is that the extropy and the entropy production are interrelated

$$\text{if} \quad \Pi > 0 \quad \text{then} \quad \sigma > 0$$

and

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and

$$\sigma = 0 \quad \text{if and only if} \quad \Pi = 0.$$

Sometimes σ is negligible in the observed time scale. σ can be very small, but it must not be zero. In the nature there are no ideal walls. They exist only in textbooks. Positive extropy leads to processes decreasing the extropy. The statement has a negative content: after a while all the extropy is lost (consumed), and there will be no further potential for changes. That is an alternative formulation of the 'heat death' notion.

The positive content of the Second Law: While there is extropy there are changes. In a system with $\Pi > 0$ there must be processes, happenings. A system with positive extropy is not a dead one. There are structures, there is functioning. That is the real content of the Second Law. The driving force of the Universe is extropy. A non-equilibrium system may exist if and only if there is an extropy input.

The extropy approach offers a new classification of the open systems.

- starving systems, where there is no extropy input. For the durable existence of a system extropy input is obligatory. The source of extropy is not the reservoir, but another system of $\Pi > 0$. When there is no input $d\Pi < 0$, after a while the system disappears.
- systems with passive input: extropy input is ensured by other system outputs. An example can be the Earth, which gets the radiation of the Sun, or an other example is a river, which gets the water from rains, brooks. In this case Π_{max} is defined by the external sources.
- systems with active inputs: the system uses one part of its extropy stock to get more extropy input, that is, the system works for the input. That is the characteristic feature of life.

Similarly, the outputs are active and passive, or voluntary and forced outputs. Some examples of active and passive inputs will be shown through the extropy balances of some important processes.

4. Extropy Balance for the Universe

Our Universe does not possess an environment, so its extropy is the difference of the actual and equilibrium entropies. Inflation is an adiabatic process, as there is no heat exchange with the environment. The 'equilibrium' entropy of the Universe changes, as:

$$\frac{dS_{U0}}{dt} = \frac{1}{T}\frac{dE}{dt} + \frac{p_0}{T}\frac{dV}{dt} > 0, \tag{24}$$

where p_0 is the 'equilibrium pressure'. The actual entropy varies, as

$$\frac{dS_U}{dt} = \frac{1}{T}\frac{dE}{dt} + \frac{p}{T}\frac{dV}{dt} + \sigma > 0, \tag{25}$$

where p is the effective pressure. The time dependence of extropy:

$$\frac{d\Pi_U}{dt} = \frac{p_0 - p}{T}\frac{dV}{dt} - \sigma > 0. \tag{26}$$

The actual pressure differs from the equilibrium one. The extropy of the Universe is increasing. Inflation creates extropy. There are model calculations for the detailed mechanism of the appearance of non-equilibrium structures [26]. The present cosmological models show that we are not approaching the 'heat death' state. The entropy of the Universe is increasing, but it does not mean the approach to an equilibrium state, as because of inflation the extropy of the Universe is increasing, too.

5. Extropy Balance for the Earth

Earth is a genuine example of the passive extropy input. For the overall picture one can neglect the heat coming from the core of Earth, and similarly the material exchanges. Then the only flow is the heat of the Sun and the heat irradiation. The surface of the Earth gets $r = 1.2 \cdot 10^{17}$ J energy in every second. The temperature of the radiation is 5704 K. The average temperature of the outgoing radiation is 287 K.

Imagine, for a moment, that the Earth is in equilibrium state! $\Pi = 0$, so $\sigma = 0$. Then the extropy balance will get the form:

$$\frac{d\Pi}{dt} = \Pi_{in} - \Pi_{out} = 4 \cdot 10^{14}\,\mathrm{J/K}. \tag{27}$$

The extropy of this hypothetical equilibrium Earth would increase. The equilibrium Earth has to go out of equilibrium. New non-equilibrium has to spring, until the entropy production will be equal to the net flux of extropy. The thermodynamic condition of the steady state is that there are non-equilibrium structures with $\Pi > 0$, ensuring the needed entropy production. This steady state has a basic stability. The change of Π is followed by the change in σ. When σ increases, then Π decreases, resulting in a decrease in σ. Gaia ensures a constant entropy production. Naturally it is valid only in the case, where the Π fluxes do not change. If the greenhouse effect modifies the radiation temperature, Gaia will find new steady state structures. This stability arising from constant entropy production is only a thermodynamic one. It is not the stability of state. For Gaia it does not matter who produces the entropy. It is only important for us! For Gaia only the balance is important. The natural and man-made processes must provide the equilibrium entropy production. We are here to produce the entropy! If we do not do it, Gaia will find other ways to ensure it. Nevertheless this continuous extropy flux is finite. The right form of the question is: which part of the total Π flux can be used by human activity. To answer this question one needs a detailed understanding of extropy balances of natural and economic processes. If we use less we will be poorer than our possibilities, if we use more we deteriorate our future.

6. Extropy Analysis for Industrial Processes

6.1. Thermodynamic Evaluation of the Production

The Second Law of thermodynamics governs industrial processes, too. Industrial processes differ from usual thermodynamic processes. Here the working environment is an artificial non-equilibrium structure. We have to create the non-equilibrium environment for the desired transformations. It means construction of the factory and maintaining of the working conditions. This is why a production process cannot be modelled as a bare transformation of the inputs to outputs. There are losses, wastes, use of non-renewable resources due to the working environment, too. Nevertheless, in first-order approximation the utility is in steady state. It does not change. The transformation metaphor can be applied.

A production process is the transformation of the inputs to outputs. The input contains the material inputs including fuel. It includes the inputs necessary for maintaining the working environment, too. The handling of capital and labour would need further investigations. The output can be divided into useful output (products and byproducts) and wastes. The First Law of Thermodynamics gives the conservation laws, namely in steady state conditions the inputs of mass and energy are equal to the outputs, as there are no sources and sinks inside the processing unit.

The extropy balance equation is (if the entropic changes in the factory itself are neglected, $\Delta\Pi_{factory} = 0$):

$$\Pi_{input} = \Pi_{output} + \sigma, \tag{28}$$

The output can be divided into useful output (product) and waste output. If $\Pi_1 =$ is the extropy of the product and $\Pi_2 =$ is the extropy of the waste, then

$$\Pi_{output} = \Pi_{product} + \Pi_{waste}. \tag{29}$$

If all the data are accessible, the above formula enables us to calculate the entropy production.

For the extropy balances the source data are the input–output tables containing the energy and material flows. For every input and output flow one has to define its form in the environment. That is the most probable natural state in the present Earth. For the most common elements this states were summarized by Szargut.

6.1.1. Example: Production of aluminium chloride

Aluminium chloride production is analyzed on the direct synthesis from aluminium metal and chlorine. The process uses melted aluminium and hot chlorine gas input which gives a slight contribution to the energy balance. Here we do not investigate the real process, but the chemical transformation. The entropy changes needed for maintaining the working conditions are excluded. The wastes and losses reflect the theoretical minimum. According to a standard source the reaction requires 220 kg Al and 800 kg chlorine to yield 1 metric ton (1000 kg) $AlCl_3$ (FAITH, KEYES & CLARK [27]$_b$). Waste streams are neglected here. Robert AXTELL and Robert U. AYRES used the desk-top version of ASPEN PLUS® called MAX® to calculate the waste stream [28]. It was only necessary to make explicit assumption about the process yield (85%), reaction temperatures and pressures and the 'candidate' waste stream compounds.

The input materials are the Al and Cl_2. Al is in the liquid state of temperature 640° C. The output is $AlCl_3$, which contains also traces of pure Al. For the sake of the present calculation we consider it as a waste. Here we show the calculations for Al.

For extropy balance one has to define the thermal and chemical terms. The mechanical terms are negligible.

$$\Pi = \Pi_{thermal} + \Pi_{chemical}.$$

Al is in the reference state, so its Gibbs energy of formation is zero. The final state is $AlCl_3$, with the Gibbs energy of formation 1581 kJ/mol. For one mole of Al the Gibbs energy difference will be:

$$\Delta G = 0 + 1581/2 = 790 \text{kJ/mol}.$$

The Gibbs energy of the mixing was determined by Szargut, it is 15 kJ/mol. It is small compared to the chemical transformation term. The chemical extropy content of 1 t of aluminium is 99.9 MJ/K.

For the thermal term we have to look for the thermal history of the aluminium. Aluminium arrives in liquid state, with the initial temperature of 940 K, the final one is 300 K. The cooling process and the solidification results in entropy changes. On solidification the heat of melting is released, and this heat is transferred to the environment. The heat of melting is Q_m, then the potential entropy production is:

$$\Pi = \frac{Q_m}{T_m} + Q_m\left(\frac{1}{T_0} - \frac{1}{T_m}\right) = \frac{Q_m}{T_0}, \tag{30}$$

where T_m is the melting temperature, while T_0 is the temperature of the environment. The heat of melting is: 387 kJ/kg. The extropy is: 387/300 = 1.3 MJ/tK.

The other term comes from the cooling of aluminium.

$$\Pi = \int_{T_0}^{T_i} C\left(\frac{1}{T_0} - \frac{1}{T}\right) dT = \int_{300}^{910} c_{Al}\frac{T - 300}{T \cdot 300}\, dT = 1.1\ \mathrm{MJ/tK}, \tag{31}$$

where T_i is the initial temperature and c is the specific heat. For the calculation we took the average value of the specific heat as 1 MJ/t.

The total thermal extropy content of the hot aluminium is:

$$\Delta G = 1.3 + 1.1 = 2.4\mathrm{MJ/tK}$$

Similar calculations were performed for Cl_2 and for the $AlCl_3$.

Π balance for aluminium chloride production

name	Π MJ/Kt	Π mixing kJ/Kt	input/ output t	Π_{tot} MJ/K	Π_{total} mixing kJ/K
input					
Al	97.6	0.46	0.22	21.40	0.12
Cl_2	17.2	1.51	0.80	13.86	1.43
output					
$AlCl_3$	9.88	1.91	1.00	9.88	2.01
Al	97.60	0.06	0.03	2.93	0.01
total input				36.26	1.55
product				9.88	2.01
entropy production				23.47	
wastes				2.93	0.01

The table shows that the mixing effects are negligible. They are of the order of magnitude of kJ/K compared to the terms MJ/K in case of thermal and chemical changes. For 1 t of $AlCl_3$ 36.26 MJ/K extropy is used. From this 9.88 MJ/K goes to the product and 23.47 MJ/K is the entropy production, while 2.93 MJ/K can be considered as waste.

The extropy balance aggregates the potential for generation of entropy in the biosphere, the lithosphere, the atmosphere, and the hydrosphere. The extropy input aggregates all the use of this potential. For $AlCl_3$ it is 36.26 MJ/K per one ton of $AlCl_3$. The part which remains in the product (byproducts) can be considered as useful. It will be used in the human activity sphere. $AlCl_3$ it is 9.88 MJ/K. The entropy production is the lost extropy. It is the thermodynamic cost of the transformation process. For $AlCl_3$ it is 23.47 MJ/K. The waste term is not a loss in the thermodynamic sense. The waste - loss distinction is of economic origin. The waste extropy means an entropy generation potential which is loaded to the environment. There it will induce changes, which are assimilated when Π_{waste} is smaller than the assimilation capacity, and it will cause modifications when it is higher. For a sustainable development we have to minimize Π_{waste}. Thermodynamics tells us that the minimum value of the waste extropy is zero. The total waste extropy can be regarded as a measure of ecotoxicity [18]. The extropy of the wastes is the potential for future entropy production of the materials loaded to the environment. It measures the physical and chemical changes induced by the wastes in the environment. When $\Pi_w = 0$, then the waste is indistinguishable from the environment, it will induce no further changes. The higher the Π_w, the more disturbances will arise. To minimize the dangers of radical uncontrolled environmental modification, it is clear that we must minimize the loss of extropy from the techno-sphere. Π_w can be used as a measure of the human impact on the environment. It is a universal thermodynamic measure. Π_w is not the usual toxicity, as it does not include biological effects.

6.2. Extropy and Economics

The present mainstream economics denies the usefulness of application of physical measures for the evaluation of economic activity. Money is a wonderful abstraction. This abstraction is both the strength and weakness of economics. The great innovation of money was its ability to serve as a universal medium of exchange, but now, increasingly divorced from real wealth, it distorts value, becomes an obstacle to intelligent choices.

Extropy can be considered as the currency for the physical world. That currency measures the direct physical exchange of energy and nutrients, with consequences of interactions that are physical—and inescapable—as well. Economic and enterprise management focused on the physical flows may yield far different insights, and performance, than management based exclusively on the abstract representations of dollars, Yen and ECUs.

Extropy measures can be developed for services, besides the characterization of the individual production steps. Here the aggregation problem does not appear. In case of joint production the extropy use can be divided between the products by the extropy contents. Summing up the extropy consumption from cradle to the service we get the total extropy cost, Π_c

$$\Pi_c = \Pi_s + \Pi_{waste} + \Sigma. \tag{32}$$

The total extropy cost is the sum of the extropy of the product + the extropy of the wastes and the total entropy production. From the thermodynamic point of view it is clear that we have to economize the extropy usage. The total extropy cost is a good candidate for the measurement of the human impact on the environment. It is a way of environmental accounting.

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References

[1] BARANYI, Á.: Thermodynamics and Economic Theory, in: Complex Systems in Natural and Economic Sciences, (eds: Martinas, K, Moreau. M.) ELFT, Budapest, p. 105, 1996.

[2] FABER, M. – NIEMES, H. – STEPHAN, G.: Entropy, Environment and Resources: An Essay in Physico-Economics, Springer Verlag, Berlin, 1987.

[3] FAUCHEUX, S. – NOËL, J.-F.: Économie des Ressources Naturelles et de L'Environnement, Armand Colin, Paris, 1995.

[4] JANKOVICH, B.: Mechanical Foundation of Value Theory (in Hungarian: Az értékelmélet mechanikai alapelveiről) *Közg. Szemle*, Vol. 35. pp. 10–23, 1903.

[5] KÜMMEL, – REINER, : Energy, Entropy – Economy, Ecology, Ecological Economics, Vol. 9, pp. 194–196, 1994.

[6] MÅNSSON, BENGT: Recycling of matter, Ecological economics, Vol. 9, pp. 191–192, 1994.

[7] O'CONNOR, M.: Entropy, structure and organizational change, *Ecological Economics*, Vol. 3, pp. 95–122, 1991.

[8] MATTHIAS, R.: Integrating Economics, Ecology and Thermodynamics, Kluwer, 1994.

[9] VAN DEN HOVE, S.: Thermodinamique des systems loin de l'équilibre en économie de l'environement, Revue Internationale de Systémique, Vol. 8, p. 4, 1994.

[10] CARLSON, R.: The Silent Spring, Boston, Houghton Mifflin Co., 1962.

[11] MEADOWS, D.– MEADOWS, D.: The Limits to Growth, New York, Universe Books, 1972.

[12] BRUNDTLAND, G.: Our Common Future, World Commission on Environment and Development, Oxford, University Press, 1989.

[13] MALASKA, P.: Nature Oriented Technology, *Turku School of Economics*, 1992.

[14] TAIT, P. G.: Sketch of Thermodynamics, p. 100. Edmonston & Douglas, Edinburgh, 1868.

[15] SZARGUT, J. – MORRIS, D. R. – STEWARD, F. R.: Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, Hemisphere Publishing Corporation, NY, 1988.

[16] MALASKA, PENNTI, JARI KAIVO-OJA: Science and Technology for Sustainable Development, *Int, Congress of Engineers and Scientists*, Challenges of Sustainable Development, Amsterdam, 1996. 22–25 August.

[17] EVANS, R. B.: A Proof that Essergy is the only Consistent Measure of Potential Work, Ph. D. Thesis, Dartmouth College. University Microfilms, Ann Arbor, Michigan, 1966.

[18] MARTINÁS, K., AYRES, R. U.: Entropy, Physical Information and Economic Values, INSEAD Working Paper, 93/05/EPS

AYRES R. U., MARTINAS, K.: Waste Potential Entropy: The Ultimate Ecotoxic, INSEAD Working Paper, 94/05/EPS,; Economie Appliquée XLVIII, 1995.

AYRES R, U., AYRES, L., MARTINÁS, K.: Eco-thermodynamics Exergy and Life cycle analysis, INSEAD Working Paper, 96/05/EPS.

[19] MARTINÁS, K.: Entropy and Information, *World Futures*, 1997. Vol. 50, pp. 483–493.

[20] MARTINÁS, K. – PASQUIER, J. L.: Extropy, an Indicator of Economic Production Impact on the Environment. A case study: French biofuel production, *Proc. of LIth Int. Conference*, Foundation Gulbenkian, Lisbon, Portugal, 1996, April 10–12.

[21] MARTINÁS, K. – CSEKŐ, Á.: Extropy—A New Tool for the Assessment of the Human Impact on environment, in: Complex Systems in Natural and Economic Sciences, (eds: Martinas, K., Moreau, M.) ELFT, Budapest, p.122. 1996.

[22] LOVELOCK, J. E.: A New Look at Life on Earth, Oxford University Press, 1979.

[23] CLAUSIUS, R.: Über verschiedene für die Anwendung bequeme Formen der Hauptgleichungen der mechanische Wärmtheorie, *Annalen der Physik und Chemie*, Vol. 125 (201) pp. 353–400, 1865.

[24] LANDSBERG, P. T.: Thermodynamics with Statistical Physical Applications, Oxford, 1961.

[25] LEBON, G. – JOU, D. – CASAS-VAZQUEZ, J.: Questions and Answers about a Thermodynamic Theory of Third Type, Contemporary Physics, Vol. 33 pp. 41–51, 1992.

[26] LUKÁCS, B. – MARTINÁS, K. – PACHER, T. :Extended Thermodynamics in the Early Universe, *Astron. Nachr.* Vol. 307, p. 171, 1986.

ALPHER, R. A.– MARX, G.: The Creation of Free Energy, Vistas in Astronomy, Vol. 35, pp 179–214, 1992.

[27] CHASE: et al., JANAF Thermochemical tables, *J. Phys. Chem. Ref. Data*, Vol. 14, Suppl. 1. 1985 Faith, Keyes & Clark, Industrial Chemicals, Wiley-Interscience, New York, 1975 p. 368.

[28] AYRES, R. U.: Economics, Thermodynamics and Process Analysis, INSEAD Working Paper, 94/11/EPS.